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Key findings of the energy performance gap in a Finnish office building

Thesis submitted for examination for the degree of Master of Science in Technology.

Espoo 19.12.2017
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Abstract

The goals set for the building sector defined in the Energy Efficiency Directive in 2016 including 27 % energy savings by 2030, increase the need for accurate energy performance evaluation of buildings from an early stage in design and decision making. While the accuracy and commercial use of BEM simulation software is constantly increasing, the gap between the simulated and anticipated consumption remains high. Closing the gap requires awareness of the major error causing factors as well as their contribution to the gap.

The aim of this study is to identify the critical factors and the magnitude of the gap for an office building in Finland, enabling the improvement of future models through focus on the factors with the highest significance. In this thesis, a case study is performed to an office building in Helsinki. Additionally, previous knowledge about the factors closing the gap as well as the magnitude of the gap are collected from previous studies and by interviewing experts.

The performance gap of the studied building is 13 %, while it is reduced to 1 % by improving the model through consideration of the most relevant factors. 15 measures are studied including ventilation, occupancy and use and technical building systems related adjustments. Ventilation adjustments, especially air flow and operation schedule adjustments of the AHUs show the highest impact on the gap, while other factors result in a minor impact. Thus, focusing especially on correct operation of the ventilation systems as well as sufficient communication between the HVAC-design team and the building users is the most critical factor in closing the gap.

Keywords performance gap, energy performance, building energy simulation

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Tiivistelmä

Vuonna 2016 julkaistun Energiatehokkuusdirektiivin asettamat tavoitteet, jotka sisältävät 27 % energian säästön vuoteen 2023 mennessä, kasvattavat tarvetta tarkalle energiatehokkuuden arvioinnille rakennuksissa jo varhaisesta suunnittelu- ja päätöksentekovaiheesta alkaen. Vaikka rakennusten tietomallia hyödyntävien simulointiohjelmistojen tarkkuus ja kaupallinen käyttö on jatkuvasti yleistynyt, ero laskennallisen ja mitatun kulutuksen välillä on edelleen suuri. Kulutuseron poistaminen edellyttää tietoisuutta tekijöistä, jotka aiheuttavat suurimman eron, sekä niiden suhteellisesta vaikutuksesta.

Työn tavoitteena on tunnistaa merkittävimmät tekijät ja kulutuseron suuruus Suomessa sijaitsevassa toimistorakennuksessa mahdollistaen tulevien mallien kehittämisen, kun niissä osataan keskittyä vaikuttavimpiin tekijöihin. Tässä työssä on tutkittu Helsingissä sijaitsevaa toimistorakennusta. Lisäksi tietoa eron suuruudesta ja syistä on kerätty aiemmista tutkimuksista sekä haastattelemalla alan asiantuntijoita.

Laskennallisen ja mitatun kulutuksen ero tutkitussa rakennuksessa on 13 %, mutta ero laskee 1%: iin, kun mallia kehitetään huomioimaan merkittävimmät kulutuseron aiheuttavat tekijät. Työssä tutkittiin viittätoista osa-aluetta, sisältäen ilmanvaihtoon, käyttäjämääriin, käyttöön ja teknisiin järjestelmiin liittyviä parannuksia. Ilmanvaihdon tarkennuksilla, erityisesti IV koneiden ilmamäärien ja käyntiaikojen tarkennuksilla on suurin vaikutus kulutuseroon, kun taas muiden tekijöiden vaikutus on vähäinen. Näin ollen merkittävin tekijä kulutuseron pienentämiselle on huomion kiinnittäminen erityisesti ilmanvaihtojärjestelmien suunnitelmien mukaiseen käyttöön sekä riittävään tiedonvaihtoon LVI-suunnitteluryhmän ja rakennuksen käyttäjien välillä.

Avainsanat laskennallisen ja toteutuneen energiankulutuksen ero, energiatehokkuus, rakennusten energiamallintaminen

Foreword

This master's thesis is written under Green Building Partners Oy, where I have had the opportunity to work with building energy simulations prior to my thesis. Thus, the issue and its relevance have been familiar to me and writing this thesis has provided me with better understanding of both the formation of the energy performance gap and the operation of the building HVAC systems in general.

I would like to thank especially my adept colleagues Simo Skogberg and Sami Nevala and my supervisor Risto Kosonen, without whom this thesis would not have been carried out. I am also thankful for all the interviewees for their collaboration by sharing their valuable expertise and thoughts about the topic.

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Espoo, December 3rd, 2017

Sofia Al-Khatib

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Nomenclature and abbreviations

BIM		Building Information Model
CAV		Constant air volume
DER		Dwelling Emission Rate
DHW		Domestic hot water
EP-value		Energy Performance value
EPG	[%]	Energy Performance Gap
E-value	[kWh/m^2,a]	The Finnish energy performance factor
HVAC		Heating, Cooling and Air Conditioning
IDA-ICE		IDA Indoor Climate and Energy simulation platform
IFC		Industry Foundation Classes
POE		Post-Occupancy Evaluation
$Q_{DHW,dw}$	[kWh/a]	Heating demand of DHW consumed by dish washing
SFP	[kW/m^3/s]	Specific fan power
U-value	[W/m^2,K]	Thermal transmittance
$V_{DHW,dw}$	[m^3/a]	Volume flow of DHW consumed by dish washing
XML		Extensible markup language
c_{pw}	[kJ/kg,K]	Heat capacity of water
nZEB		Nearly Zero Energy Building
q_{exp}	[kWh]	Expected energy consumption
q_{obs}	[kWh]	Observed energy consumption
ΔT_w	[°C]	Temperature difference between hot and cold domestic water
ρ_w	[kg/m^3]	Density of water

1 Introduction

1.1 Background and motivation

The building sector is responsible for 40 % of the energy consumption and 36 % of the CO_2 emissions in Europe making buildings a significant factor in the target of reducing global energy consumption and emissions. According to the estimate of the European Union, 5–6 % of the total energy consumption and 5 % of the CO_2 emissions in Europe can be reduced by increasing the energy efficiency of both new and existing buildings. (European Commission 2017a.) In the Energy Performance of Buildings Directive (EPBD), the targets set for energy efficiency of buildings include 20 % reduction in both energy and CO_2 consumption by 2020 compared to the level of year 1990 (European Commission 2010). Furthermore, the targets are increased to 27 % savings by year 2030 in the proposal for an updated EPBD (European Commission 2016).

Increased interest of energy efficiency has led the way to the calculation of target energy consumption of buildings using the available design parameters. Despite their relatively high accuracy, these estimates are not a direct reflection of the measured energy consumption of the operational phase. Great uncertainty is involved especially, when predictive modelling techniques are used with limited feedback of verified performance (Fedrouk et al. 2015). The accuracy of initial information used in the model compared to the actual operation, the proper operation of building systems and the modeler affect the mismatch between the target energy consumption and the measured consumption.

When the designed operation is not realized in the building, it may possibly lead also to a poorer indoor environment than planned. The indoor environment affects the users' health and well-being, since people spend 90 % of their time indoors (Klepeis et al. 2001). The so-called "performance gap" is thus not only an economical issue for building owners and tenants when the consumption is underestimated, and unexpected energy costs occur. Insufficient ventilation reduces also well-being and productivity resulting in additional costs, despite the saved energy.

Residential buildings cover over 85 % of the Finnish building stock, thus dominating the total energy consumption of buildings. Office buildings represent 0.7 %. (Statistics Finland 2015.) Two thirds of the energy consumed in residential buildings is used for supply air and space heating due to the cold climate with low outdoor temperatures the major time of the year. Other significant end uses are domestic hot water and receptacle equipment as shown in Figure 1. (Statistics Finland 2017.) Moreover, Figure 2 shows the share of energy end-uses in office buildings, where the facility and tenant equipment cover one third of the total energy consumption while the share of heating is reduced (Kurnitski 2011). The unrealistic modelling of the parameters affecting the major end uses, supply air and space heating, are also the most significant factors in the performance gap.

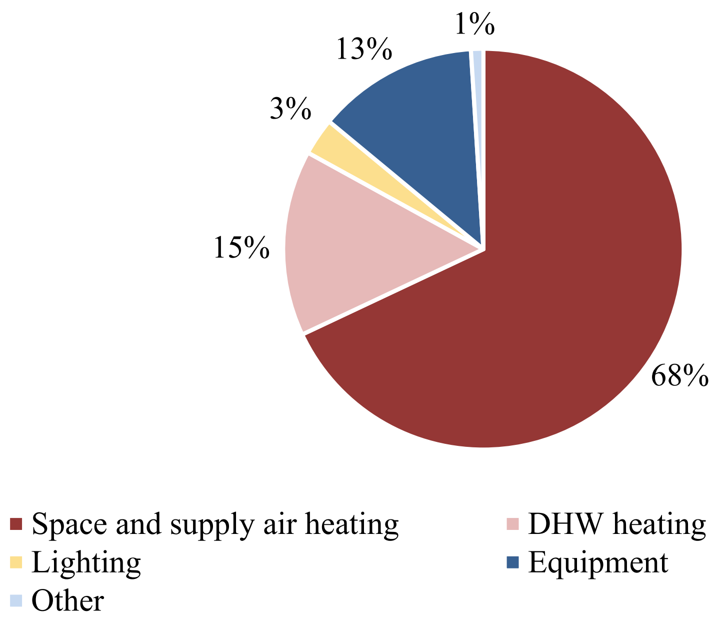

Figure 1. Energy consumption of residential buildings in Finland by end use in 2016 (Statistics Finland 2016).

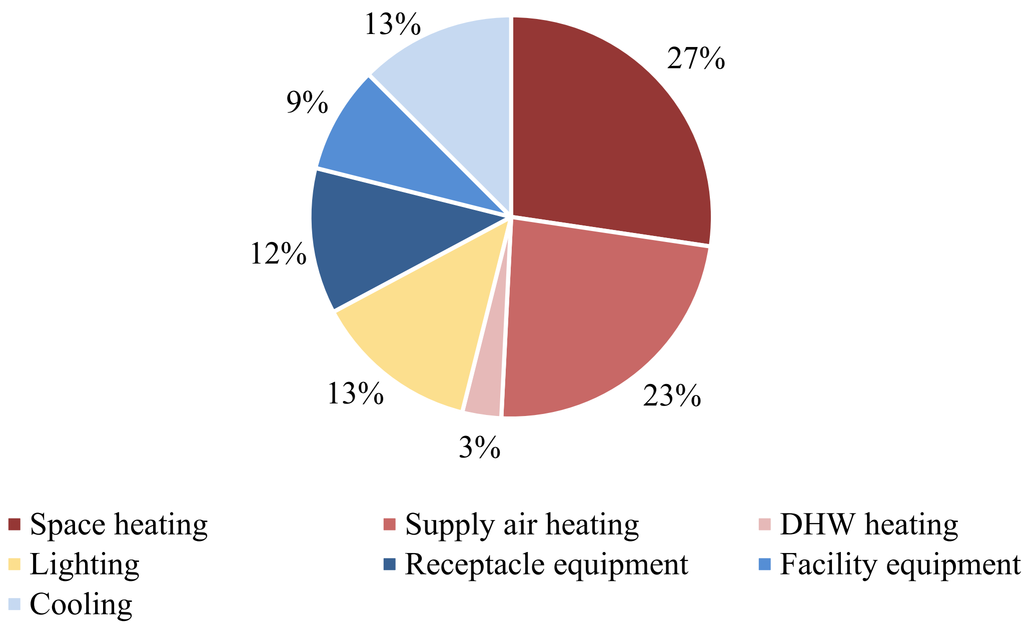

Figure 2. Energy consumption of office buildings in Finland (Kurnitski 2011).

When the metered consumption can be as high as 2.5 times the estimated energy consumption, the reliability of the energy simulation is questionable (De Wilde 2014). Closing the gap between the predicted and measured energy consumption is important especially when reliable outcomes are needed from the design stage energy modelling. High reliability is needed to quantify the energy performance of buildings with a high expected performance, such as nZEBs, Zero Carbon and Low Energy buildings.

1.2 Aim of the study

This study investigates the known factors affecting the energy performance gap based on previous publications to gain a wide perspective on the issue. In addition, experienced energy experts working with the Finnish building stock are interviewed to widen the perspective on the current issues on the energy performance in Finland. A case study is performed for a Finnish office building, aiming to find factors in the model reflecting the mismatch of the estimated and metered energy consumption. The thesis focuses on office buildings in Finland, since they have relatively well-known occupancy schedules reducing the impact of unpredictable occupant behavior and enabling the focus on technical use and systems.

The aim of the study is to identify the magnitude of the energy performance gap firstly in previous studies and secondly through interviews with modelers possessing previous experience on target energy consumption modelling. Thirdly a case study is performed for an office building in southern Finland. Additionally, identification of the major reasons for the energy performance gap is pursued based on the literature review, the interviews and the case study.

The case study is performed with the IDA-ICE simulation software, and the results are compared to the measured energy consumption. Consistently, the results from the case study are compared with the previous studies and with the outcomes of the interviews, aiming to find similar factors affecting the performance gap.

However, the aim of the study is not to identify all factors affecting the performance gap, but to find the ones with the greatest impact. The available design documentation is used to create the target energy consumption model, which is further compared to the operation and consumption of the actual building. Individual investigation of the differing factors is performed obtaining the magnitude of the specific effects of each factor.

However, the constrained building sub-metering as well as the building automation transparency set limitations to the investigation. Therefore, only part of the significant factors can be examined in the study, and there is a performance gap even after the model is improved. Possible reasons for the remaining gap are aimed to be identified. Finally, the target of the study is to conform the target energy consumption calculations by naming the major error causing parameters, thus increasing also the quality of the calculations. This study acts as a base for further investigation and improvement of the energy performance estimates.

1.3 Structure of the report

The report consists of nine chapters. Chapter 2 presents the relevant standards and regulations in building energy performance and design parameters both in European level and in Finland. In addition, the mainly used simulation software and measurement methods are introduced. Chapter 2 discusses also the definition of the energy performance gap and gives an overview of the previous studies performed on the topic.

The used study methods and the main outcomes from the literature review are presented in Chapter 3, while the methods and the outcomes of the performed interview are explained in Chapter 4. In Chapter 5 the specific features of the studied case building are presented together with the obtained target energy consumption results and the magnitude of the energy performance gap as well as issues related to it. To further investigate the reasons for the performance gap, multiple potential factors affecting the gap are studied separately by changing only the single factor in the model. In Chapter 5 each studied parameter and their individual and combined effects on the simulation model are explained as well.

Chapter 6 summarizes the results from the case study regarding the magnitude of the performance gap and the effects of the studied parameters. The findings from the literature review, the interviews and the case study are discussed in Chapter 7. Finally, Chapter 8 consists of conclusions.

2 Building Energy Performance

2.1 Standards and regulations

In the 2010 Energy Performance of Buildings Directive (EPBD) the European Union (EU) has agreed on increasing the energy efficiency of buildings by 20 %, reducing CO_2 emissions by 20 % and increasing the share of renewable energy sources by 20 % from the level of 1990 by the year 2020 (European Commission 2010). As a follow-on, a new policy for the time period 2020-2030 is defined in the updated Energy Efficiency Directive (EED) in 2016. The new targets are 27 % energy savings compared to the current level, a 27 % share of renewable energy sources and a 40 % reduction in the CO_2 and other greenhouse gas emissions from the level of 1990 by the year 2030 (European Commission 2014).

The global Paris Agreement came into force in Finland in the end of 2016 as in most of the EU countries. The aims of the agreement are settling the increase of the average global temperature under 2 °C from the pre-industrial level, adapting to the adverse effects of the climate change and economically enhancing the market towards low-emitting solutions. These goals are proposed to be updated to the EPBD by the European Commission in 2016. (European Commission 2017a.)

In order to enhance the market of energy efficient buildings and increase the awareness of the consumers about the energy efficiency of buildings in the real estate market, the EU requires each building to be evaluated by its energy performance. An energy labeling procedure with classes from A to G is described in the 2009/125/EC and 2010/30/EU directives. The Commission suggested a review in the directives regarding energy labeling in 2015, and in 2016 it updated in the EPBD that the energy efficiency certificates are mandatory for all buildings in the market. (European Parliamentary Research Service 2016.)

Based on the EPBD and the SFS standards in Finland, the building energy performance and the related building systems are prescribed in the Finnish Building Code sections D2, D3 and D5. The section D2 introduces the requirements for ventilation and indoor environment quality. It requires the building design and ventilation to ensure a healthy, safe and comfortable indoor environment in all occupied spaces. The design temperature for most occupied spaces is recommended to be 21 °C and it should not exceed 25 °C during the occupancy period. In addition, the ventilation system should be monitored and controlled according to the air quality and occupancy level. (The Finnish environmental institute 2012a.)

In Finland, adequate filtering is required, when mechanical ventilation is used. The current minimum requirement for the supply air filter defined in the Finnish Building Code section D2 is level F7, but a new requirement according to the SFS-EN ISO 16890 standard will be ePM_1 50 - 65 %. (Jalkanen et al. 2017.) Section D2 provides recommendations for the air flow rates for commonly used space types, of which some are presented in Table 1. These recommendations together with the heat loss calculations are used in sizing of the HVAC systems and therefore represent an essential part in the energy consumption of the building. The Finnish Ministry of the Environment together with FINVAC ry (2017) have suggested an update to the air flow recommendations shown in Table 1.

Table 1. The recommended air flow rates by space type for most typical space types according to section D2 (The Finnish environmental institute 2012a) and the suggestion for new recommendations (The Finnish Ministry of the Environment and FINVAC ry 2017).

Space type	**Outdoor air flow D2 [dm³/s,m²]**	**Exhaust air flow D2 [dm³/s,m²]**	**Outdoor air flow suggestion [dm³/s,m²]**	**Exhaust air flow suggestion [dm³/s,m²]**
Office	1.5	-	1.5	-
Conference room	4	-	3	-
Corridor	0.5	-	0.5	-
Classroom	3	-	3	-
Lobby	2 - 4	-	3	-
Sports hall	2 - 6	-	2 - 6	-
Restaurant	5 - 10	-	3 - 6	-
Kitchen	5 - 15	5 - 15	-	5 - 15
Kindergarten rooms	2.5	-	2.5	-
Sales area	2	-	1 - 3	-
Storage	-	0.35	0.35 - 1	-
Restroom	-	20 - 30 / seat	-	20 / seat

Section D3 of the Finnish Building Code concentrates on energy performance rating and determination. It explains the procedures of calculating the total energy consumption of a building and introduces various prescriptive indicators for heat loss determination in buildings. Additionally, the system boundary of the building energy consumption is determined as shown in Figure 3, including the delivered energy needed by the building and its technical systems and excluding the exported energy (The Finnish environmental institute 2012b).

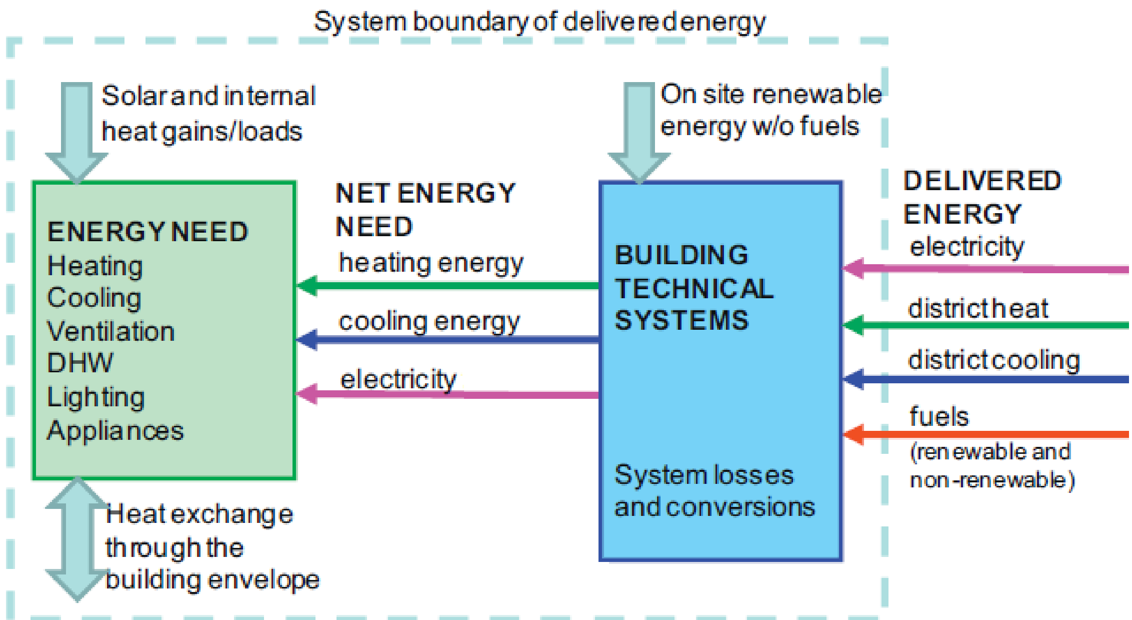

Figure 3. The system boundary of the building energy system (The Finnish environmental institute 2012b).

In section D3 the E-value is introduced as an energy performance metric similar to the EP value defined in the EPBD. The E-value is used in comparing the energy performance and energy efficiency of buildings. However, it is widely acknowledged that the E-value is not a good representation of the actual energy consumption due to the energy performance factors included in the calculation and the simplifications of the calculation method (VTT 2012). Instead, the designed and assumed operation of the building should be used when calculating the target energy consumption of the building.

More specific guidelines for heating load and energy consumption calculations are determined in section D5 of the Finish Building Code. For buildings with cooling demand, an hourly calculation method is required whereas for buildings with only heating demand a monthly calculation is sufficient. (The Finnish environmental institute 2012c.)

Due to the cold climate, heating is one of the major end-uses in Finnish buildings. Therefore, an airtight and well-insulated building envelope is required to reduce the heat loss and thus also the heating demand. Section D3 of the Finnish Building Code prescribes the thermal conduction properties such as the maximum allowed and the typically used reference U-values of the structures as presented in Table 2 (The Finnish environmental institute 2012b).

Table 2. The maximum allowed and typical U-values of the building envelope (The Finnish environmental institute 2012b).

Structure	**Maximum U-value [W/m²,K]**	**Typical U-value [W/m²,K]**
External wall	0.6	0.17
Roof	0.6	0.09
Slab-on-grade floor	0.6	0.16
Door	1.8	1.0
Window	1.8	1.0

By the beginning of 2018, the Finnish construction requirements will be renewed to respond to the nZEB target set in the delegated regulation N:o 244/2012 of the European Union (European Commission 2012a). The new requirements are supposed to be applied in the buildings applying for a construction permit after 1.1.2018. The main designed changes concerning energy efficiency relate to improved ventilation heat recovery (HRU) efficiency and SFP value requirements. Additionally, the energy source factors and requirements concerning the E-value will be adjusted towards the national nZEB level. Achieving the nZEB level will be determined by reaching a lower E-value than the defined limit. (Ympäristöministeriö 2016.)

2.2 BIM simulation tools

The Building Information Model (BIM) is a 3D model created from the architectural drawings or 2D drawings of the building. The BIM created by the architect is typically too heavy for energy performance simulation purposes, since it consists a great amount of irrelevant information. Therefore, a light BIM is typically created by the energy modeler in order to reduce and speed up the energy simulation process. (Pietarila 2013.)

A Building Information Model is needed for performing hourly energy demand calculations and determining the hourly indoor temperatures and temperature constancy. Estimation of the cooling demand involves a great uncertainty exposing the calculation to significant errors (Pietiläinen et al. 2007). In addition, it is usually covered with valuable energy, the consumption of which building owners and tenants want to be aware of. Therefore, a dynamic hourly simulation is required for buildings with cooling demand in order to obtain more precise calculation results. Buildings with no cooling demand do not require an hourly simulation and a simplified monthly steady-state calculation according to the EN ISO 13790 standard and the section D5 of the Finnish Building Code is sufficient. (The Finnish environmental institute 2012c.) However, dynamic calculation is necessary also when weather dependent RES and energy storage systems are used.

The Royal Institute of Technology in Sweden published in 1963 one of the first dynamic simulation software BRIS utilizing a numerical solution for solving simultaneous energy balance equations for various air nodes and surfaces. With the development of the computation engines and the increased interest in energy consumption due to the energy crisis, hundreds of dynamic simulation software were developed, such as the currently commonly used DOE-2.1E, Energy Plus, IDA-ICE and ESP-r. (Jokisalo 2008.) In Finland, the most common commercial dynamic simulation software are IDA-ICE and RIUSKA (Pietiläinen et al. 2007).

The IDA Indoor Climate and Energy (IDA-ICE) is a detailed dynamic simulation tool considering all relevant physical phenomena as modelled thus providing a reliable simulation platform. The general IDA simulation tool was developed by the KTH using BRIS for verification of the program (Jokisalo 2008). The IDA-ICE is an extension created for IDA and it is currently able to perform simulations for natural, hybrid and demand control ventilation as well as comfort, control optimization and system analysis (EQUA 2017). IDA-ICE is commonly used in Scandinavian countries amongst consultants and research organizations (Ingrid 2015). Therefore and due to its highly validated accuracy, it is chosen as the second simulation software for the case study.

The modelling software use objects in representation of building parts and their format cannot be directly interpreted to the simulation software. Therefore, a format that is supported by both the modelling and the simulation software is needed when transferring the BIM from the modelling platform such as AutoCAD to the simulation platform. Such formats are typically IFC and XML. Industry Foundation Classes (IFC) is an object-orientated model identifying the object components and describing their behaviour and relations. (Pietarila 2013.) The IFC format is used between AutoCAD and IDA-ICE in this study.

2.3 Energy consumption measurement

In order to have comprehensive understanding of the operation of the building systems and find the adjustable parameters, an inclusive metering system should be available in the building. In Finland, at least a main electricity meter and a main heating meter measuring the purchased heating energy are required for all buildings according to the Finnish Building Code section D3. Additionally, a main domestic hot water (DHW) meter as well as separate electricity meters for ventilation and cooling systems are required for all buildings except small residential buildings. Lighting shall also be metered separately in all other but residential buildings. (The Finnish environmental institute 2012b.) In addition, various sub-meters for different building systems or building sectors can be found in new buildings.

(Pietiläinen et al. 2007.) The more detailed and inclusive the sub-metering is, the more reliably various modelling input parameters can be determined and the easier modelling errors are spotted.

The Energy Efficiency directive of the European Union 2012/27/EU requires a main meter for electricity, natural gas, district heating, district cooling and DHW in new and renovated buildings wherever it is cost-efficient. Starting from 2016, tenant-specific submeters for electricity, heating, cooling and DHW are also required when they are technically possible to install. (European Commission 2012b.) In 2014 the EU has set a target to replace 80 % of the electricity meters with smart meters by 2020 wherever the replacement is cost-efficient. The aim is to reduce energy consumption and emissions by adjusting supply and demand. (European Commission 2017b.) However, the replacement of electricity meters is not mandatory but rather a proposal for the member states.

Electricity is metered primarily for billing purposes and therefore the main meter is located in the building's connection point to the grid, and submeters are available for all tenants of the main building. For other than industrial buildings, electricity is metered typically as hourly active power consumption. (Pietiläinen et al. 2007.) Electricity can be metered as a spot measurement, run-time measurement, short-term monitoring and long-term monitoring depending on the metering purpose. The applications advantages and disadvantages of each monitoring method are presented in appendix 1. (Parker et al. 2015.)

Purchased district heating and cooling are measured with flow meters such as the water consumption. The flow meters measure the liquid flow at a certain time interval or convert it to energy consumption at a certain time interval (Parker et al. 2015). Typical flow meters for building applications are vortex shedding flow meters, differential pressure meters, displacement and magnetic meters (Chattopadhyay 2006).

The building automation system collects the data from various measurements and operates the system accordingly aiming to maintain the indoor temperatures, energy consumption and system operation in the desired levels. The metered data is stored in the automation system from where it can be used in energy consumption and system monitoring as well as finding the possible malfunctions in the system. (Pietiläinen et al. 2007.) In addition to the building automation system, the metered data is often logged directly into a separate energy monitoring system such as EnerKey and Nuuka, which allows remote monitoring of the building performance.

In order to standardize and ease the operation of the building automation system, a European standard for remote reading of building meters M-Bus (Meter-Bus) was developed in The Paderborn University in Germany. It consists of the physical and link layer EN 13757-2 and the application layer EN 13757-3 and is currently a widely used interface in Europe. The purpose of M-Bus is to support the building automation system by enabling remote reading and networking of the data collected from the building systems. (Ziegler 1998.)

In addition to direct energy measures, supporting measures such as indoor temperatures, air flows at the air handling units and occupied spaces, pressure differences between the indoor and outdoor air, floor temperatures and CO_2 concentration can be measured helping to understand, weather the HVAC systems are operating according to the design. The air tightness of the building envelope can be determined by measuring the air flow needed to maintain the 50 Pa reference pressure difference between the indoor and outdoor temperature. (ATTMA 2010.) The air tightness is measured manually as a single time measurement.

The metering is not always accurate, but in order to deliver reliable information its accuracy has to be sufficient. According to the section D2 of the Finnish Building Code the air flows of the air handling units and the heating and cooling power may not differ by more than 10 % from the design value including both value variation and metering inaccuracy. (The Finnish environmental institute 2012a).

2.4 Performance gap

The energy performance gap is defined as the difference between calculated and measured energy consumption of a building including its full complexity regarding sub-systems, controls, occupant behaviour and climate (De Wilde 2014). The energy performance gap can be studied in various resolutions the most typical being a yearly level. Other possible resolutions are for example monthly, weekly or daily.

The Zero Carbon Hub (2014) has ranked the issues related to the performance gap in four categories according to their evidence from the literature review and questionnaires performed and their impact on the performance gap as shown in Figure 4. The categories with low impact on the performance gap require no immediate action, whereas the categories with high impact on the performance gap either require further research or can be considered with currently available information (The Zero Cabon Hub 2014).

The relation of the impact of actions on the performance gap and their total cost is divided into four categories presented in Figure 5. The actions rated with the highest impact were effective commissioning strategies, management training, inclusion of consultants in the design process and applying metering strategies. On the contrary full dynamic modelling, Post Occupancy Evaluation and feasibility studies were considered as actions with relatively low impact. (Carbon Trust 2012.)

The performance gap can be roughly divided into a procurement gap and an operational gap. The procurement gap is defined as the mismatch between the calculated performance during the design stage and the verified normalized metered performance. On contrary, the operational gap is caused by the deviations in the predicted and realized occupants' behaviour, building operation and climate. It describes the difference of the metered verified consumption and the non-normalized performance. (Ingrid 2015).

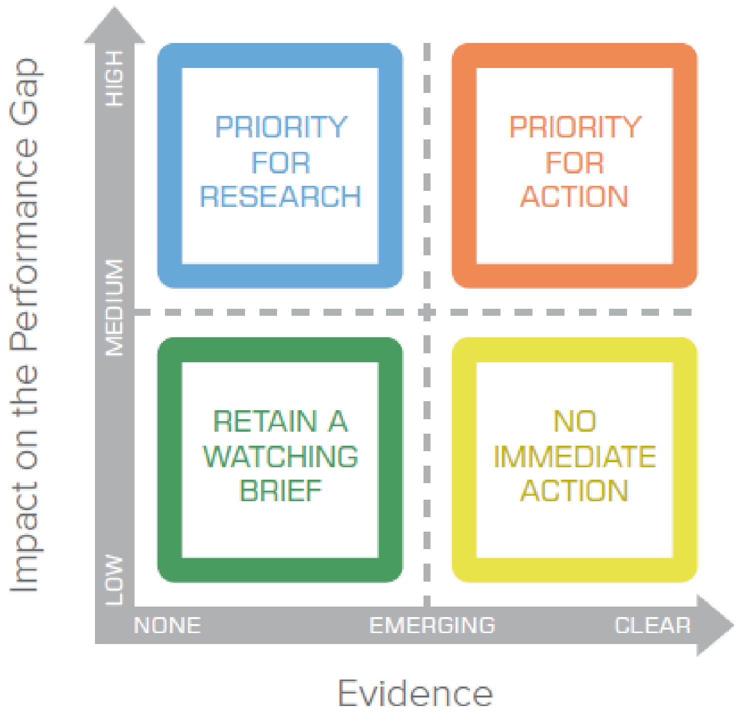

Figure 4. The issue categories related to the performance gap according to the prioritisation matrix approach (Zero Carbon Hub 2014).

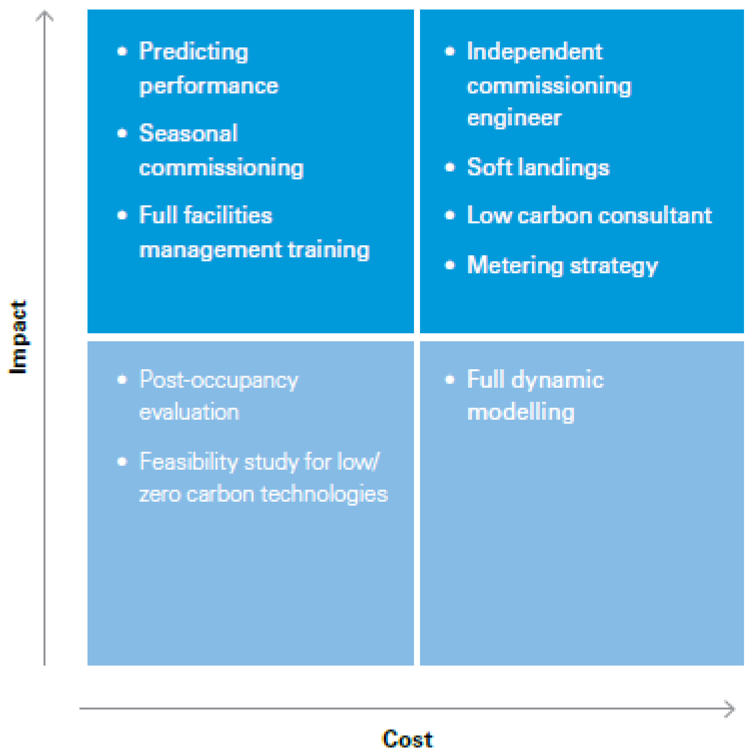

Figure 5. The total cost and impact of actions aiming to reduce the performance gap (Carbon Trust 2012).

The procurement gap can be further divided to issues related to the construction phase and the operational phase (De Wilde 2014). In addition, the operational gap can be divided into the comfort gap and wrong assumptions about the technical systems of the building. The comfort gap occurs due to the occupants' behaviour depending on their intentions to save money or increase their personal comfort level. The comfort gap of new constructions is relatively arbitrary due to the unpredictability of the occupants' choices and behaviour. (Cali et al. 2016.)

The fundamental gap between the estimated and measured energy consumption can be examined from various perspectives as shown in Figure 6. While prediction methods highlight the heating cooling load, the measurements include also the impact of plug loads, occupant behavior and climate variation. Therefore, a performance gap between the prediction and measurement is inevitable. This is further expressed as shift between the normative methods utilized in the prediction and the public display. Machine learning can be used as a tool for decreasing the gap during the operation with the help of frequent measurements. (De Wilde 2014).

The estimated consumption is determined during the design phase performing stationary, semi-dynamic or fully dynamic simulations. During the operation stage, the consumption is measured within the building by at least one meter, but typically multiple meters and submeters. According to the measured performance, adjustments can be made to the energy simulation model in order to obtain more reliable results. (De Wilde 2014).

The energy model can be recreated during the operation phase for adjustment of the actual building operation to the model and for examination of possible effects of different operation strategies. However, the energy consumption calculated after the corrected input parameters or applied machine learning methods is no longer an estimate of the design phase and the performance gap can therefore not be determined as a difference between the corrected estimate and the measured consumption. The actual performance gap is calculated according to equation 1, where q_{obs} [kWh] is the observed metered energy consumption during a certain time period and q_{exp} [kWh] is the expected consumption estimated during the design phase including all the technical features such as heat recovery (Cali et al. 2016).

$$EPG = \frac{q_{obs} - q_{exp}}{q_{exp}} \tag{1}$$

A slight mismatch between anticipated and measured consumption occurring from numerical errors in the simulation and measurement accuracy is inevitable (De Wilde 2014). It is also harmless in understanding the energy performance level of the building. The aim in examination of the performance gap is to minimize the difference to a level with a low relevance.

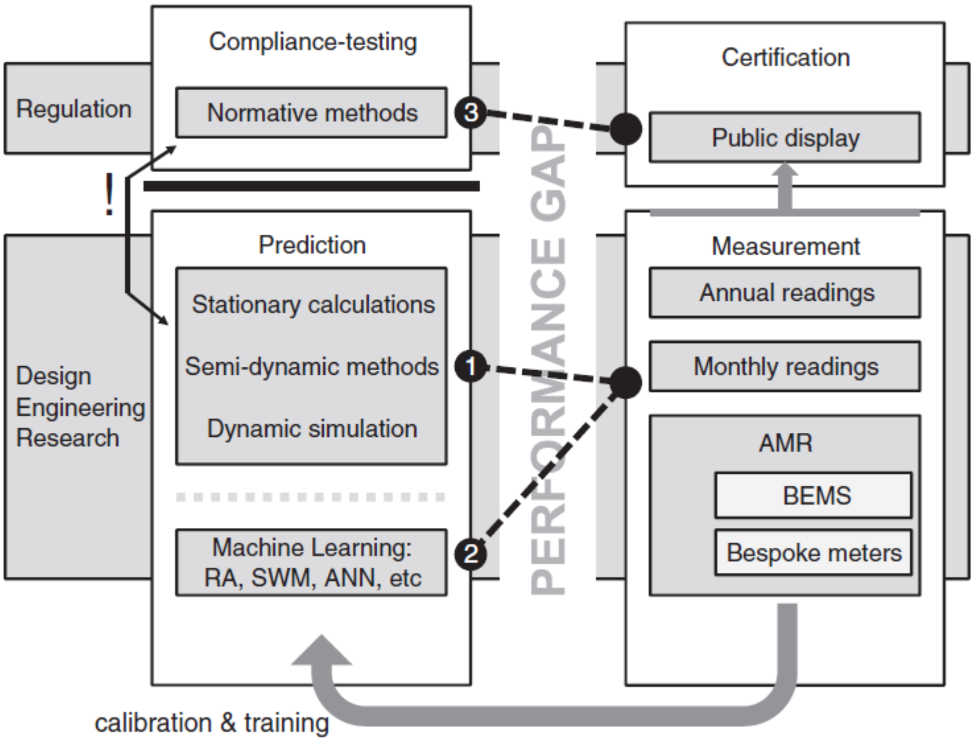

Figure 6. The various views related to the performance gap (De Wilde 2014).

3 Literature review on energy performance gap

3.1 Literature review method

A capture of previous studies is investigated and the magnitude of the performance gap and major reasons for it are collected in Chapter 3.2. The aim is to form a comprehensive understanding of the available information on the performance gap and form a platform for the case study and interviews as well as further studies on the topic. The factors with highest impact on the gap based on the literature are summarized in Chapter 3.3.

The studies included cover both scientific papers and previous master's thesis. While the majority of the performed studies are located in Great Britain, studies from Finland and other European countries are included to gain wider perspective. All relevant building types, such as offices, educational, residential and industrial buildings are represented in the literature review. Each study, however, is performed in a unique manner and the studies are thus not fully comparable. Additionally, various simulation programs are used such as IDA-ICE and Energy Plus resulting in slightly different calculations.

3.2 Previous studies

The energy performance gap in buildings is studied in various papers before. However, the findings of the studies are not straightforward and multiple reasons are accused for the performance gap. The studies are not entirely comparable due to different building types, locations, study methods, levels of details and building and occupant specific features. Nevertheless, they provide an informative platform for further investigation.

One of the first studies is performed by Bordas et al. (2001) studying 23 buildings in Great Britain through Post Occupancy Evaluation. Two other British studies, the Zero Carbon Hub (2014) and Carbon Trust (2012) cover in total 125 buildings from multiple occupancy categories. These studies are altogether the widest studies on the topic but leave still gaps on the detail level.

The issues behind the mismatch vary between different buildings, but they can be roughly divided to issues in the design phase, the construction phase or the operational phase (De Wilde 2014). In the design phase the issues can be caused by the lack of communication between the design team and the client or inside the design team (Fedrouk et al. 2015). An incorrect prediction of the building use as well as operational requirements can also affect the estimates, since often the tenant is not known (Salehi et al. 2015). The design itself may cause incorrect estimates of the energy consumption, when the building technical systems are poorly or unrealistically designed or contain only few details (De Wilde 2014).

In the design process the modelling and simulation errors pose a significant risk in obtaining the correct results (De Wilde 2014). The use of complex systems does not guarantee accurate calculations. Instead, it increases the uncertainty and the possibility for errors. The proper understanding and knowledge of the building systems as well as occupants' behaviour is crucial to obtain reliable results. However, such information is often unavailable during the design stage and the occupant behavior may change also during the operation period. The impact of the modeler is generally underestimated due to the difficulty of their quantification. Imam et al. (2017) found an error in estimated energy consumption varying from +18 % to -50 % compared to a verified model, which indicates a great effect of the educational level, experience and personal ideas of the modeler to the result. The effect of the modeler can also be noted from the study of Fedrouk et al. (2015), since the major reasons for the differences are claimed to be a poor boundary definition and incorrect design assumptions in addition to inaccessible information.

The report of the Zero Carbon Hub (2013) suggests that there is a poor link between the model and the reality, when no audit from the actual performance and verification is applied by modelers. Furthermore, the fundamental uncertainties regarding weather conditions, internal heat loads and schedules and plug loads are hard to model precisely, and therefore are part of the factors affecting the performance gap (De Wilde 2014). Should these factors be modelled correctly, the calculation shall be updated during the operation period has begun.

During the construction stage issues related to the performance gap can occur from weaker performance of systems than designed due to selection of components with lower costs but higher energy consumption, or generally from building properties such as insulation and airtightness not corresponding to their specification. Part of the details, such as thermal bridges, is typically left to the contractors' choice and is therefore partly unknown to the designers. Such choices after the design phase can affect the airtightness, especially in new construction, and other building thermal properties causing a building operation different from the designed. (De Wilde 2014.) Issues during the construction and commissioning phase are often difficult to measure and identify, especially with lack of communication and interaction between the different groups. The poor communication and feedback during the commissioning are highlighted in the study of Fedrouk et al. (2015).

The issues during the operation phase have been noticed in the majority of studies. The unpredictability of occupancy schedules and thermal loads, especially in buildings with unclear or varying occupancy schedules such as residential and educational buildings, is a relevant factor causing performance gap, but relatively difficult to quantify. The occupant and property maintenance behaviour related to operation of appliances and thermal loads is addressed as one of the most significant factors for example in the studies of Kampelis et al. (2017), Salehi et al. (2015) and Ingrid (2015). De Wilde (2014) suggests, that plug loads are often overestimated due to technological development and constantly reduced demand of appliances. However, other studies such as Kampelis et al. (2017) and Fedrouk et al. (2015) show an underestimation of plug loads.

The predictability of occupant behaviour is studied in Ahn et al. (2017). The study shows that the occupant behaviour especially in building types with no constant schedule cannot be predicted reliably resulting in errors in predictions of the internal gains from people, lighting and plug loads as well as ventilation. In certain building types such as offices occupants typically have access to manual controls such as the indoor temperature controls affecting the operation of the technical systems of the building (De Wilde 2014). In Finland however, the access to manual controls is rare.

Stochastic models predicting the behaviour of occupants have been developed for office buildings and households, where the schedules are relatively constant and predictable. However, the models still remain as better estimates and do not describe the reality precisely. Moreover, they are not suitable for all building types and there is a need for improved occupant prediction models especially for other building types than offices, residences and dormitories. (Ahn et al. 2017)

Post Occupancy Evaluation has been suggested to improve the level of operation of the building, thus reducing the gap resulting from operational malfunctioning (De Wilde 2014 and Menezes et al. 2011). POE can be further utilized in evaluation of the building performance during its entire life-cycle as suggested in the Värkki project of FGBC (2013). The effect of the POE is studied in a British study of PROBE (Post-occupancy Review of Buildings and their Engineering) with 23 case studies. The outcome from the study addressed the lack of feedback from occupants' behaviour during the operational stage as the main reason for the performance gap. (Bordass et al. 2001.) Increased feedback form realized behaviour increases the level of the performed estimates in future projects.

The performance gap in general has been widely investigated in the British studies of Zero Carbon Hub and the Carbon Trust. The Zero Carbon Hub studied 97 cases observing an average performance gap of 17 %. It concluded the reasons for the performance gap to belong to three categories: lack of knowledge, communication and management. (Zero Carbon Hub 2014.) 28 buildings of various building types were also studied in the study of Carbon Trust indicating an average 16 % underestimation of the energy consumption and highlighting the lack of feedback as the driving factor (Carbon Trust 2012).

In Finland the performance gap is studied using a black box method based in the regulations of the Finnish Building Code and the electricity metered by the electricity providers in the study of Ruusala (2015). In the black box method, the building systems are not analyzed, but an estimation on the energy consumptions is made based on the building type, dimensions and main systems. This rough estimate is compared with the metered energy consumption. The study showed an average overestimation of 41 % in the total energy consumption. However, the E-value calculation is not a target energy consumption estimate as it is not calculated according to the actual design and operation, and therefore the study can't give reliable explanations for the performance gap. It indicates great errors in the calculations, which are probable to occur also in the target energy consumption estimate calculations. A more precise study performed by Nevala (2015) shows that the performance gap can be up to 25 % based on an actual target energy performance simulation and metered data.

3.3 Literature outcome

The majority of the previous studies show an underestimation in the energy consumption with a magnitude up to 178 %, and only few have a relatively small performance gap or overestimation of the consumption, as seen in appendix 2. In office buildings, the performance gap varies from -2 % to 30 %. Based on these studies, the performance gap is a fundamental problem in the building performance evaluation, and procedures for closing the gap need to be established and standardized to provide comparable and reliable estimates of the energy performance level of buildings.

Poor communication resulting in lack of useful information during the design phase was addressed in most studies as a significant factor increasing the performance gap. Additionally, Kampelis et al. (2017), Fedrouk et al. (2015) and Zero Carbon Hub (2014) concluded that lack of communication during the commissioning phase resulted in a different use of technical systems than designed, causing a typically increased measured energy consumption. Nevala (2015) found that alongside with abnormal operation of technical systems, poor exploitation of building automation systems resulted in a reduced efficiency of the technical systems increasing especially the electricity consumption.

The false use of technical systems and reduced exploitation of the automation systems affects especially the fan and pump electricity as concluded in the study of Fedrouk et al. (2015), where the measured consumption was 184 % higher than predicted mainly due to sequences of operation varying between the design and application. Pumps consumed also nearly twice as much electricity than predicted in the study of Salehi et al. (2015).

When creating the simulation model, the most significant errors occurred from false prediction of occupancy behaviour and schedules as addressed in Kampelis et al. (2017), Menezes et al. (2011) and Carbon Trust (2012). Different occupancy behaviour resulted typically in increased heating demand as well as electricity consumption, especially when occupants had manual access to lighting and plug loads. De Wilde (2014) highlighted false estimate of plug loads as the major reason for the performance gap.

Studies regarding only office buildings concluded slightly less importance on the occupancy behaviour. According to Ahn et al. (2017), predictability of occupancy behaviour in office buildings and other buildings with relatively regular occupancy schedules is easier than in other building types resulting in more reliable calculation results. On contrary, in the studies of de Wilde (2014) and Menezes et al. (2011) regarding only office buildings, the importance of the magnitude of the plug and lighting loads was increased. The magnitude of lighting and plug loads is naturally a significant factor also in other building types such as educational buildings, as addressed in Fedrouk et al. (2015) and Salehi et al. (2015).

However, it should also be noted that even the measured energy performance might be incongruent with the actual energy performance due to metering faults or lack of metering as experienced in the study of Fedrouk et al. (2015). This difference is difficult to detect when working with metered data from the POE and should be considered in the reliability of the meters and the metering system.

4 Interview of experienced modelers

4.1 Interview methods

Five experts in the Finnsh energy modelling field are interviewed regarding the energy performance gap in Finnish office buildings. Each of the experts represents a different company or institution, which enhances the variety of answers and thus provides a relatively wide and comprehensive understanding of the currently realized malfunctions of the target energy consumption calculations.

The experts are asked about their experience on the term and topic of the energy performance gap. Additionally, their educational background, modelling experience and previously used energy simulation software are surveyed for better understanding of the relation between the answers and the current experience level.

Evaluation of the average energy performance gap in Finnish office buildings and the main reasons for the performance gap are surveyed both directly and indirectly. The indirect questions concern availability of various initial data needed for the simulation in draft design, final design and commissioning phases. In cases, where some relevant initial data is unavailable, the experts are asked, how they form estimates and whether those estimates are based on the building regulations, previous experience or other possible sources.

The subjective opinions of the modelers are asked about the most difficult parts to consider when creating a target energy consumption model. The observed details that are challenging to match between reality and in the model are surveyed together with the experience on actual tracking of realized energy consumptions during the operating stage and updating the simulation models accordingly.

All the interview questions are presented in Appendix 3. The questions can be divided into questions about previous experience on the gap, availability of information at different stages and previous experiences on the magnitude and reasons of the energy performance gap. The responses of the interviewees are analyzed together by subject in the following chapters.

4.2 Previous experience on the performance gap

All the interviewed modelers have more than five years of experience on the energy performance gap, on average over 11 years (Jokisalo 2017, Kovanen 2017, Larsson 2017, Nevala 2017, Vuolle 2017). They represent professionals with different educational levels varying from Bachelor of Engineering to Doctor of Science and with different working positions including researching, consulting, management and CEO. Additionally, each of them represents a different company or institution. With the variety of backgrounds of the interviewed experts, different opinions and findings can be included into this study and taken into consideration in future models.

When asked about their previous experience on the performance gap, the majority of interviewees claim to have robust experience on energy model creation through personal practice, but partly also through reflection of models made by other professionals. Additionally, most modelers have experience on monitoring the anticipated energy consumption during building operation and comparison of the initial target energy consumption model to the metered consumption. However, the term “performance gap” is not much in use as such and therefore appears slightly unfamiliar (Kovanen 2017, Jokisalo 2017).

The most used energy simulation software amongst the interviewed modelers is IDA-ICE, which is used by each interviewee. The interviewees value in IDA-ICE its versality, formability, development, support and suitability even for complex research. However, complexity and long processing time are seen as a disadvantage. The Riuska software is also rather much in use and it is complimented for its quick performance whereas its downsides are perceived to be simplicity and limited performance. Other used software include IES-VE, Sefaira, Trnsys, Ventac and ESP-R. (Jokisalo 2017, Kovanen 2017, Larsson 2017, Nevala 2017, Vuolle 2017.) Regardless of the software in use, the modelers observe a mismatch between the simulation and reality.

4.3 Availability of data and assumptions

All interviewees agree that from the information needed for calculating the target energy consumption, not all relevant information is available. Generally, the available information includes the geometry of the building, construction materials and other architectural, HVAC and electrical drawings (Jokisalo 2017, Larsson 2017). More precisely during the preliminary design stage, precursory design documents including the scope of the building, initial ventilation solutions and serving areas of air handling units and possibly lighting power estimates are available (Nevala 2017).

During the final design stage available inputs are the final air flows and ventilation serving areas, a more specific space type division and sometimes the simulated lighting powers. Finally, ventilation fan powers, applied lighting powers and possibly the air tightness of the building envelope are available at the commissioning phase. (Nevala 2017.) Kovanen (2017) addresses that all models are created for one specific scenario, since the eventual tenants, the number of users and the actual use of the building cannot be comprehensively predicted.

Information that is generally not available for calculation of the target energy consumption include time schedules and occupancy profiles related to users, lighting and equipment. In addition, DHW consumption and technical details of special spaces such as server rooms, kitchens and cold rooms, are often unavailable. (Jokisalo 2017, Larsson 2017.) In the preliminary design phase, the space type information, space division and indoor air quality targets are incomplete (Vuolle 2017). Sizing powers for technical systems including ventilation and electrical heating and melting systems, as well as final lighting powers and occupancy are also unavailable during the preliminary design phase (Kovanen 2017, Nevala 2017).

Most relevant information is available in the final design stage, but the actual operating schedules of air handling units, especially during night hours, are unavailable. Since the tenant is not known, the exact equipment information and interior heating loads and schedules are unknown. The precise interior heating loads remain unavailable even in the construction phase, and additionally actual setpoints of air controlled systems and relevant metering documents are unknown. (Kovanen 2017, Nevala 2017, Vuolle 2017.)

According to all interviewees the major difficulties in creation of the target energy consumption model are related to estimation of the missing information. Especially factors that are not known during the entire process and that vary between different buildings, even when they are of the same type, such as office buildings, create a great uncertainty (Jokisalo 2017). Such factors are lighting, equipment and occupancy densities and profiles, which are related to the building use (Kovanen 2017, Larsson 2017, Vuolle 2017). In addition, factors associated with process loads and process energy consumption including server centers, facility kitchen and refrigeration units as well as electrical window and driveway heating systems remain often under estimates (Nevala 2017, Vuolle 2017). Another difficulty in the model creation is correct consideration of buildings with complicated shapes and structures and with large openings (Nevala 2017).

Among the difficulties related to the energy performance gap is estimation of factors that are manipulated during the actual use of the building, such as indoor temperatures, which can be altered by the building users. Additionally, the consumptions resulting from the inaccuracy of these adjustments and occasionally also estimated definition of the building zones increase the uncertainty of the calculations. (Kovanen 2017, Nevala 2017.) On contrary, the simulation software are generally very precise in static heat loss calculations and heating demand calculation. They are so precise, that they calculate for instance utilization of internal heat gains in an optimal manner, whereas in practice the processes are not ideally controllable. (Nevala 2017.)

While most information available in the design documents is used when building the target energy consumption model, information gaps are filled mostly with well-informed estimates based on the experience about previous cases (Jokisalo 2107). Such estimates include often power information and schedules about lighting, receptacle equipment, de-icing networks and pumps as well as general building use profiles (Kovanen 2017, Larsson 2017, Nevala 2017, Vuolle 2017). Some unavailable information such as efficiencies of distribution networks and cold bridges is estimated using the Finnish Building Code, but generally the Building Code is avoided in creation of estimates (Nevala 2017). Other possible sources for estimates are space type specific user profiles proposed by FINVAC and ASHRAE (Kovanen 2017, Larsson 2017).

However, even the information available in the design documents does not necessary describe the actual building operation and therefore the metered or surveyed information is more reliable than the design documents (Jokisalo 2017). The available information at the design phases and the construction phase together with the base of estimates used to fill the information gap are described in Table 3.

In order to improve the estimates, the metered consumptions and inspection of the building during operation are used to compare the simulation and the actual simulation and find the mismatches. When asked about the observed difficulties in calibration of the model, the interviewees highlighted that submetering is often insufficient to track the mismatch into exact subsystems. The possible unwillingness of tenants to hand over their consumption data complicates the tracking of error functioning of the building, such as simultaneous heating and cooling. (Nevala 2017, Vuolle 2017.)

Table 3. The information available at each phase and the base of estimates used to evaluate the missing information (Jokisalo 2017, Kovanen 2017, Larsson 2017, Nevala 2017, Vuolle 2017).

Phase	Available	Unavailable	Base of estimates
Preliminary design	Building scope, initial ventilation solutions and serving areas, initial lighting powers	Space types, IAQ targets, sizing powers for technical systems	Preliminary design documents, Finnish Building Code, Previous experience
Final design	Specific space division, final air flows and ventilation serving areas, simulated lighting powers	Actual operating schedules of AHUs	Final design documents, Finnish Building Code, Previous experience
Construction	Ventilation fan powers, final lighting powers, air tightness of the envelope	Actual setpoints of air controlled systems, relevant metering documents	Final design documents, Metered or surveyed information, Finnish Building Code, Previous experience
All	Building geometry, construction materials, architectural, electrical and HVAC design documents	Schedules and profiles for lighting, occupancy and equipment, DHW consumption, technical details of special spaces (server rooms, cool rooms, kitchen)	Design documents, Finnish Building Code, Previous experience

4.4 Acknowledged deficiencies in the energy model

All interviewers agree that the average performance gap of office buildings in Finland is high and rough estimates of an average 20 - 40 % performance gap is suggested (Nevala 2017, Vuolle 2017). In detailed research projects on the topic, a gap down to 1 % can be reached. Initially all models are incorrect, but some of them are better estimates than other. The magnitude of the gap depends on the reasons of the mismatch, including the creator of the model, the used estimates and the actual building use. (Vuolle 2017.) The creator of the model influences the level of accuracy in the model, which can result from the inaccuracy and lack of initial information or resource constraints. (Vuolle 2017, Larsson 2017.)

The difference between the assumed and the actual building use can also conclude in a significant mismatch of the energy consumptions (Jokisalo 2017). In addition to interior heat gains, the actual use affects the ventilation schedules, indoor temperature setpoints, operating schedules and other adjustments made eventually by the janitor, which may differ from the design (Vuolle 2017). However, each case is different and depends on the functioning of the technical systems as designed. The malfunctioning of technical systems has a higher effect in buildings, where the systems have a significant role, such as buildings with high air flows. (Jokisalo 2017.)

A mismatch is caused also through ideal simulation patterns not reflecting the actual systems. In practice, the systems are not ideally controlled according to the internal loads, which is shown as malfunctioning of the technical systems such as simultaneous heating and cooling in a space. (Nevala 2017).

Target energy consumption is calculated mainly for non-standard buildings. For standard buildings, the energy consumption estimates are often estimated based on area or volume dependable values from existing buildings or the consumption of the previous year, which may not form a reasonable reference. (Nevala 2017.) The possibilities enabled by using the created energy models are often not considered during the commissioning phase. Additionally, there are lacks in communication between the involved parties. (Kovanen 2017.)

The observed reasons for the energy performance gap can be divided into four subcategories, which are modeler dependent, initial information dependent, user dependent and software or model dependent. The factors related to each category are presented in Table 4.

Table 4. The factors affecting the energy performance gap by subcategory (Jokisalo 2017, Kovanen 2017, Larsson 2017, Nevala 2017, Vuolle 2017).

Category	**Factors**
Modeler dependent	Incorrect or inaccurate modeling of systems
Initial information dependent	Insufficient design documents (especially operating schedules, end use and occupancy); Design documents not reflecting the actual operation
User dependent	Lack of communication between the designer, the building owner and the end-users; Use and operation of the building different from designed or estimated (indoor temperature setpoints and operating schedules of ventilation and other technical systems); Choice of construction materials, equipment and lighting fixtures; Malfunctioning of systems (i.a. simultaneous heating and cooling)
Software / Model dependent	The building is treated as ideal system by the model

The lack of submetering results in the inability of searching properly the reasons for the performance gap (Nevala 2017). Eventually, there is no correctly operating building, since the building design documents are formed based on estimates and cannot predict the actual operation of the building, which in turn depends on the building users, the activity of the janitor, the chosen construction materials, equipment and lighting fixtures (Vuolle 2017).

5 Case study

5.1 Study methods

The energy performance of a representative office building is investigated aiming to identify its performance gap and the main reasons for it. The target energy consumption of the building during its second operating year from November 2016 to October 2017 is simulated with a fully dynamic simulation software IDA-ICE using the information available in the final design phase. Hence, the target energy consumption simulation is performed according to its definition. The weather data of the reference year 2012, created based on the weather data of the years 1981 – 2009, is used in the energy simulation (The Finnish Environmental Institute 2011a). Therefore, the metered consumption is normalized to correspond with the weather of the reference year.

The target energy consumption case is created using as much available data as possible from the final design phase documents, especially architectural, HVAC and electrical documents. The information gaps are filled with the guidelines of the Finnish Building Code and previous experience of best practices in similar buildings. Since during the design phase not all the necessary data is known, the model is disposed to uncertainties and errors.

The basic information is obtained from the design documentation regarding space division to air handling units, supply and extract air flows rates and target room air temperatures. Additionally, information on possible controls and designed schedules for lighting and technical systems supplement the model. The accuracy of the simulation and the magnitude of the performance gap reflects the level of available information from the design documents. Therefore, the available information is utilized to its maximal extent, however only with a level of detail used in the typical target energy consumption models.

The measured energy consumption is collected from an online platform EnerKey with the remote readable metering data from the building. The collected data includes the logged data from the main electricity, heating and cooling meters as well as DHW meter. Additionally, metered energy consumption is logged from multiple submeters including separately building and tenant lighting and equipment electricity for each tenant, HVAC electricity and cooling production electricity.

The data from submetered energy consumptions helps the identification of the false estimates. Apart from the metered consumptions, the actual building operation and use is examined and compared with the design. HVAC and lighting operating schedules, setpoint temperatures and supply air temperatures and schedules are collected from the building operating system and they are presented in tables 6 – 8. Additionally, the building occupancy level is surveyed from the building owner and the applied lighting fixtures are included in the model. Operational malfunctioning or poor exploitation of automation is considered, when significant performance gaps are found in certain consumptions.

When the simulations for the target energy consumption are performed, the detailed results are compared with the metered consumptions firstly at a rough level where the differences in heating, cooling and electricity demand are identified. Where significant differences are observed, the correlation of available submetered systems, information from the building operation system and simulation are analyzed to locate the probable reasons for the mismatch. The investigated parameters and their hierarchy are described in Figure 7.

Furthermore, the following 15 measures and combinations are adjusted in the model individually observing their effect on the gap.

- Ventilation operation schedules
- Constant air flow with minimum flow rates
- Constant air flow with minimum + 20 % flow rates
- Supply air and indoor temperature setpoints
- Heat recovery temperature efficiency
- Occupancy rate
- Occupancy density
- Lighting density
- Equipment power density
- Domestic water heating
- Heating distribution methods
- Cooling network pumps
- Combined ventilation adjustments
- Combined use and occupancy adjustments
- All adjustments combined

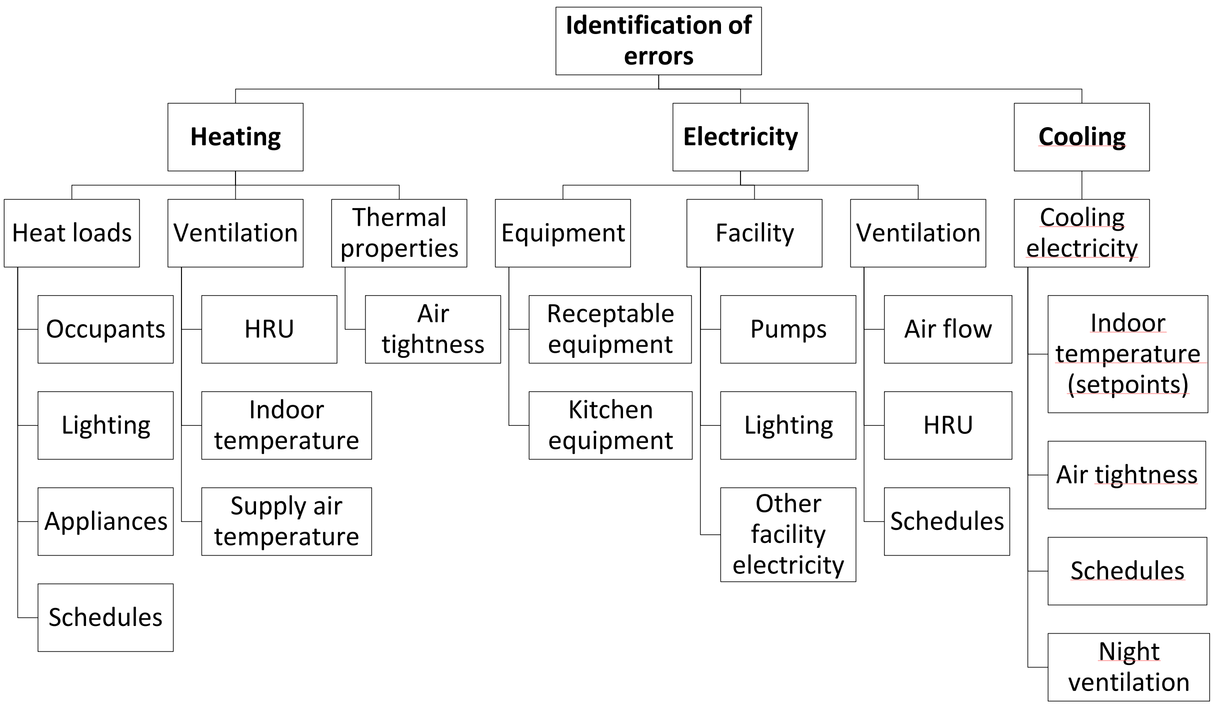

Figure 7. The studied parameters and error identification procedure.

To further investigate the errors of the target energy consumption and verify the findings, multiple simulation cases are performed. Each case provides an individual study of the effect of each parameter with significant observed difference from the information or assumption used in the target energy consumption. In investigation of each parameter, the missing or incorrect information is adjusted to the model and the resulting effect on the performance gap is documented.

Finally, all the parameters are adjusted together into a new model representing the actual building as accurately as possible with the available information. The gap between the corrected model and the actual consumption is reported together with the gaps of the individual parameters. The final model represents more accurately the anticipated energy consumption than the initial target energy consumption simulations.

Nevertheless, the actual performance gap can only be calculated from the first simulation models, where no information of the metered data is utilized. The first simulation represents the situation during the design phase, when the target energy consumption is calculated. Equation 1 is used for calculating the energy performance gap. Additionally, the difference of each adjusted simulation and the metered consumption is calculated for comparison purposes.

Should the mismatch between the simulated and measured energy consumption be further reduced, the differences in operational and technical details can be more closely analyzed. A realistic model with sufficient accuracy can be obtained through an iterative process repeating the simulation, comparison to the metered consumptions and correction of the model. However, since there are limitations in the submetering and occupancy information, the manual calibration of the model is limited and would require wider continuous measurements in the building. Since the aim of the study is to identify only the major error causing factors, the final simulation with relatively similar simulated and metered energy consumption is sufficient to this extent.

5.2 Case introduction

The case building constructed in 2016 is located in Helsinki and has a total heated floor area of 15 472 m^2 consisting of eight floors and an unheated parking garage of 3 640 m^2 in two basement floors. However, the parking garage is left outside the study scope. The building represents a typical modern office building, since most of the spaces are office spaces and meeting rooms. Additionally, there is a restaurant space combined with a kitchen in the first floor. The building is LEED certified and has therefore focused considerably on energy related measures and water consumption of fixtures.

All the building structures including windows are designed according to the minimum requirements of the Finnish Building Code section D3 and have therefore thermal properties as presented in Table 2. In practice, the U-values may not precisely represent the designed ones, but the difference is assumed to be insignificantly small. Additionally, the thermal bridges of the building are assumed to reflect thermal conductivities in section D3 of the Finnish Building Code. The estimated infiltration rate (q_{50}) of the building is 1.0 m^3/ m^{2}s.

Since the building consists primarily of offices, the estimated main occupancy schedules are from 8.00 to 17.00 in the weekdays excluding summer holidays, when the average occupancy during the occupied hours is assumed to be 24 %. These schedules are applied in the office spaces for occupants, lighting and receptacle equipment. In the restaurant, the occupancy is assumed to settle between 11.00 and 13.00, whereas irregularly occupied spaces such as restrooms and storage rooms are modelled without occupants.

The spaces are divided into several air handling units according to the occupancy purpose of the spaces and the designed AHUs. All the office spaces are served by constant air flow air handling units operating from 7.00 to 18.00 that is from one hour before occupancy until one hour after. Those air handling units have both heating and cooling capacity and in the design documents their heat recovery temperature efficiency is defined to be 80 % with rotating heat recovery units. Conference rooms have a separate air handling unit with variable air flow controlled by the CO_2 concentration. This air handling unit is provided with rotating heat recovery, heating and cooling and has similar operation period as the air handling units of the office spaces.

Separate air handling units are designated to the restaurant dining area and the kitchen space. The air handling unit serving the dining area has similar properties as the air handling unit of the conference rooms, but has additional night time ventilation for reduction of cooling demand and better indoor air quality. The kitchen is served by a constant air flow air handling unit operating from 6.00 to 16.00 provided with heating and cooling coils and a liquid heat recovery with an estimated temperature efficiency of 50 %.

Restrooms and break rooms are provided with constant air flow air handling units with heating, cooling and liquid heat recovery units. The air handling units operate from 6.00 to 16.00 and have additional night time ventilation. Other spaces are provided with constantly operating exhaust air ventilation. All the air handling units have an estimated SFP of 1.8 kW/m^3s except the air handling units with exhaust ventilation only, which have an estimated SFP of 1.0. kW/m^3s.

The air handling units, lighting and other technical systems are controlled by the building automation system. Part of the lighting is controlled with occupancy sensors while part is manually or schedule controlled. The meeting rooms and restaurant dining area are designed to have CO_2 censors coupled with the corresponding air handling units.

There is additional electricity consumption in the building that does not need to be modelled directly into the simulation model, but it shall be considered in the total electricity consumption. Such electricity is estimated for the operation of circulation pumps, de-icing networks, lifts, IT servers and rainwater sewer heating equipment. The losses from the heating, cooling and hot water network are also considered according to the Finnish Building Code.

The building is connected to the district heating network and all heating demand including domestic hot water is covered with purchased district heat. Heat is distributed through air conditioning and radiative heating and cooling panels with average heating capacity of 23 W/m^2 and cooling capacity of 24 W/m^2 in other but the first floor and basement floors, which have floor heating and auxiliary spaces with water-circulated radiator heating. Cooling is produced locally with water chillers and it is distributed through the heating and cooling panels and through supply air with the help of cooling coils. The electricity is purchased from the local supplier through the local electricity grid.

Since the exact occupancy rates are not known, they are estimated according to each space type and their typical user density, being 14 – 16 m^2/person in regularly occupied spaces. Naturally, using estimates expose the model to errors, but since more accurate information is not available during the design phase, such estimates are needed. The domestic hot water consumption is calculated according to section D3 of the Finnish Building Code. For the office building type, it is 103 dm^3/m^2 yearly.

There is lack of information regarding the studied building at the time of the initial target energy consumption calculation. The unavailable information consists of exact knowledge about the air handing unit operation, such as heat recovery efficiency and SFP, unknown occupancy rates and schedules as well as unknown domestic water consumption. Additionally, other electricity consumption is uncertain and roughly estimated.

Most of the missing information is available after the building has begun its operation and it can be used for finding the false estimates. However, it cannot directly be used to improve the target energy calculation model, since the information is not available before operation. The findings can be used for formation of estimates for buildings with similar properties and occupancy purpose, and thus improving the future simulations.

5.3 Energy performance gap

The simulated target energy consumption of the studied building represents the estimated energy consumption, while the metered consumption represents the actual consumption of the building. Hence, the energy performance gap is the difference between the target energy consumption and the normalized metered energy consumption. In the studied case building the total metered energy consumption is 13 % greater than the simulated target energy consumption. The majority, 94 % of the gap occurs from the difference in heating energy as shown in Figure 8.

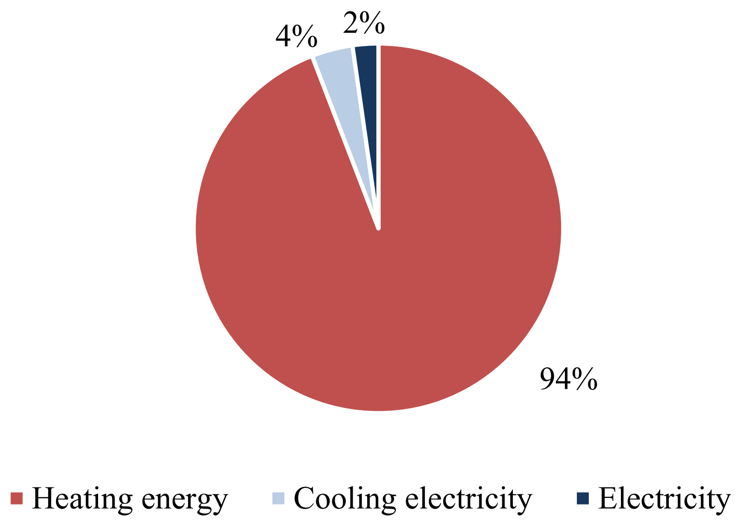

Figure 8. The share of the differences in heating, cooling and other electricity consumptions in the total performance gap.

The gap can be further investigated under electricity, heating and cooling demand as presented in Table 5. The greatest gap is in the heating energy consumption, which differs in total by 33 %. Cooling energy differs by -13 % and the net difference of other electricity consumption is -1 %. It should be noted that cooling electricity is metered and simulated as electricity instead of general cooling energy consumption and thus the possible differences in the COP of cooling are not accounted.

Table 5. The breakdown of the performance gap by subconsumptions.

	Target energy consumption	**Normalized metered energy consumption**	**Preformance gap**	
	kWh/m²a	kWh/m²a	kWh/m²a	%
Heating energy	**49.3**	**65.6**	**16.2**	**33 %**
Space and AHU heating	41.5	62.3	20.7	50 %
DHW heating	7.8	3.3	-4.5	-58 %
Cooling electricity	**4.6**	**4.0**	**-0.6**	**-13 %**
AHU cooling	1.3	0.8	-0.5	-38 %
Space cooling	3.3	3.2	-0.1	-4 %
Electricity	**67.3**	**66.9**	**-0.4**	**-1 %**
Fans	12.8	8.5	-4.3	-34 %
Pumps	4.4	6.9	2.5	57 %
Facility equipment	6.9	9.4	2.5	36 %
Facility lighting	2.6	5.1	2.5	94 %
Tenant equipment	28.4	26.6	-1.8	-6 %
Tenant lighting	12.1	10.4	-1.8	-14 %

According to the available submetered energy consumptions, the total electricity can be divided into fan, pump, lighting and receptacle equipment electricity. Additionally, heating can be divided into space heating and domestic water heating, and cooling can be divided into space cooling and cooling of supply air. The breakdown of each subconsumption and their individual performance gap is presented in Table 5. The relative difference between the target energy consumption and the normalized metered consumption is the greatest in building electricity use including lighting, equipment and pumps as well as in space heating energy. Likewise, the lowest difference is in supply air cooling and occupant equipment.

On annual level, the total gap of the case building is 236 MWh that is 15 kWh/m^2. Furthermore, the difference in heating energy is 16 kWh/m^2, in cooling energy -0.6 kWh/m^2, and in electricity 0.4 kWh/m^2. On a monthly level, the greatest differences are during winter months November, December and January with heating energy as the driving factor. On contrary, the months with the best matching total energy consumption are June and August, with differences mostly in cooling and ventilation electricity. In Figure 9 are presented the consumptions of each energy type monthly for both the simulated and the metered consumption.

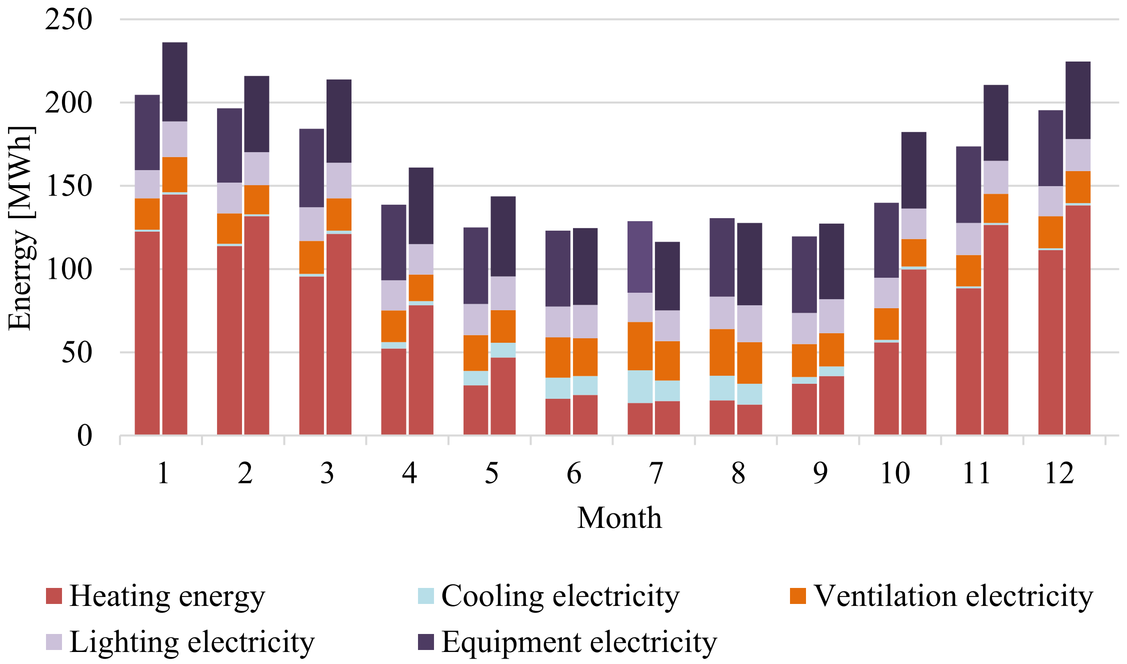

Figure 9. The monthly simulated and metered energy consumptions of the case building. The left column represents the simulated and the right column the normalized metered consumption.

As can be seen from Figure 9, heating energy covers the majority of the total energy consumption being also the most significant energy type in the gap formation. On contrary, cooling electricity is the least significant consumption type in the gap formation since it has the lowest magnitude. Equipment electricity covers the majority of the electricity sector in both the target energy consumption and the metered consumption, while ventilation and lighting electricity consumptions are relatively equal, minor electricity consumers.

Although the metered and simulated energy consumptions differ in every subconsumption in almost every month, the overall distribution of the consumptions is similar in both cases as can be seen from Figure 9. The total consumption is highest during winter months and lowest during the summer period. Heating is emphasized from October to April, while cooling is nearly insignificant. Furthermore, cooling is concentrated from May to September, when heating is the lowest. Electricity consumption is nearly constant throughout the year, but a slight increase in ventilation electricity can be identified from May to September in both the simulated and metered consumptions. However, the difference is merely visible in the scale of Figure 9.

5.4 Studied parameters influencing the performance gap

5.4.1 Ventilation

Ventilation schedules

In the design phase, the operation schedules for each air handling unit was defined in the design documents according to the estimated use of the spaces and the local building requirements. However, during the commissioning phase and beginning of the building use, the operation schedules needed to be defined into the building automation system. In the studied building the applied operating schedules for the air handling units did not fully correspond to the designed ones. The designed and the actual operation schedules of the AHUs are presented in Table 6.

Table 6. The designed and actual operating schedules of the air handling units.

AHU	Designed operation	Actual operation	Weekly difference in operating hours
301TK - 303TK Offices	MON - FRI 7 - 18 and 24 - 07 night ventilation	MON - FRI 7 - 18, no night ventilation	- night ventilation
304TK Kitchen	MON - FRI 6 - 16 and 16 - 6 at 50 %	MON 4 - 16, TUE 5.30 - 16, WED 5.30 - 19, THU 5.30 - 20, FRI 5.30 - 16	- 24 h
305TK Restaurant	MON - FRI 7 - 18	Same as in 304TK	+ 6 h
306TK Auxiliary spaces	MON - FRI 6 - 16 and 16 - 6 at 50 %	MON - WED 3.45 - 19.45, THU - FRI 3.45 - 22.45	+ 1 h
307TK Restrooms	MON - FRI 6 - 16 and 16 - 6 at 50 %	MON 2.45 - 19.15, TUE - FRI 3.45 - 19.15, SAT - SUN 9 - 19	+ 13.5 h
308TK – 310TK Stairway	MON - SUN 24h	MON - SUN 7-21	- 70 h
311TK Technical spaces	MON - FRI 7 - 18	MON - SUN 7-21	+ 43 h

The applied operation schedules correspond in no air handling unit and the actual operation is generally longer than the designed operation. In the office AHUs, night ventilation was suggested to be used between 0 am to 7 am from Monday to Friday in order to decrease the indoor temperature in the beginning of the space occupancy, thus reducing the cooling demand. Nevertheless, in the actual operation, no night ventilation was introduced. The initially modelled night ventilation operation of the air handling units 301TK – 303TK is presented in Figure 10. The night ventilation is on during the night hours, when the return air temperature is at least 23 °C and the outdoor temperature is at maximum 12 °C. During its operation the supply air temperature setpoint is reduced by 10 °C for heating and increased by 20 °C for cooling in order to decrease unnecessary heating and cooling of the supply air.

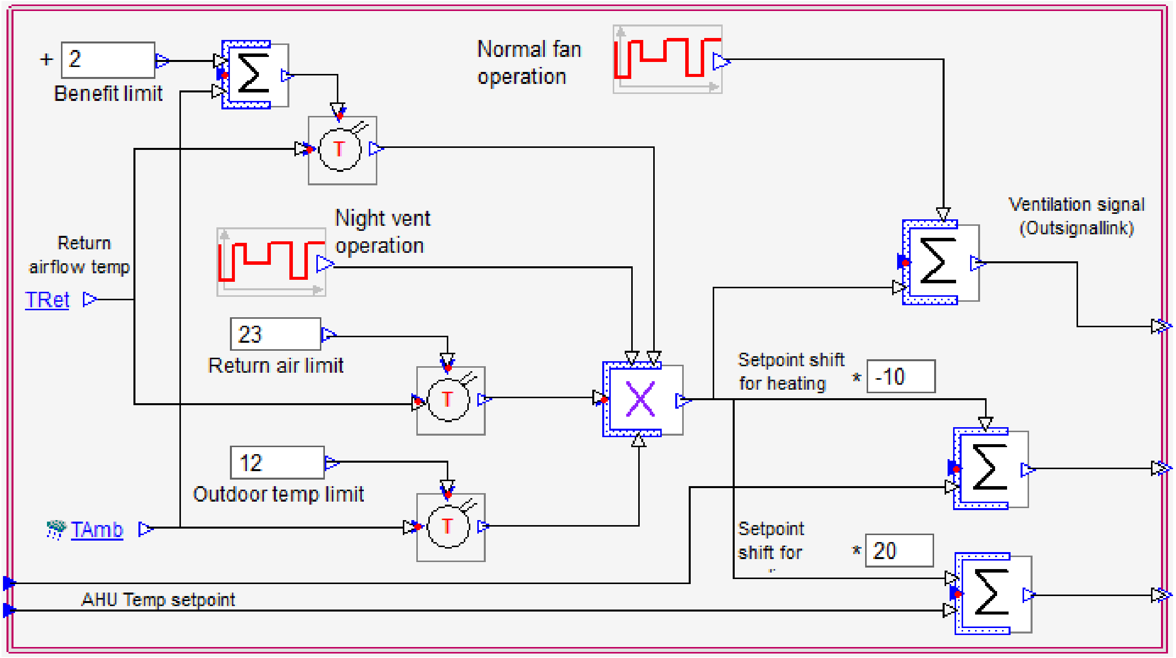

Figure 10. The macro for the designed operating procedure of night ventilation in air handling units 301TK – 303TK.

Since the operation schedules differ as presented, the space and supply air heating, space cooling and supply air cooling as well as fan electricity differ between the target energy consumption and the simulated consumption with adjusted operation. All other end-uses are equal to the target energy consumption. The relation of the energy consumption with adjusted operation of the air handling units to the target energy consumption and normalized metered energy consumption is presented in Figure 11.

For AHU systems operating with part load, the fan power depends on the air flow. With lower air flow rates, the fan power is reduced approximately at the power of three. The relation between the air flow and the fan power set by default in the modelling software is assumed to be higher than in the actual fans resulting in underestimation of the fan power demand.

The heating energy and fan electricity of the adjusted case correspond more with the metered consumption than the initial simulation case. The fan electricity, in particular, is close to equal to the metered fan electricity. The space and supply air heating are increased compared to the target energy consumption, but have a lower mismatch with the metered consumption than the initial case. On contrary, the differences of the simulated and metered consumptions in space and supply air cooling are increased due to the adjustment. The adjusted model has a 14 % higher total energy consumption than the metered consumption due to the significantly increased heating consumption resulting from mainly increased operation periods of the AHUs especially during evening hours with low outdoor temperatures.

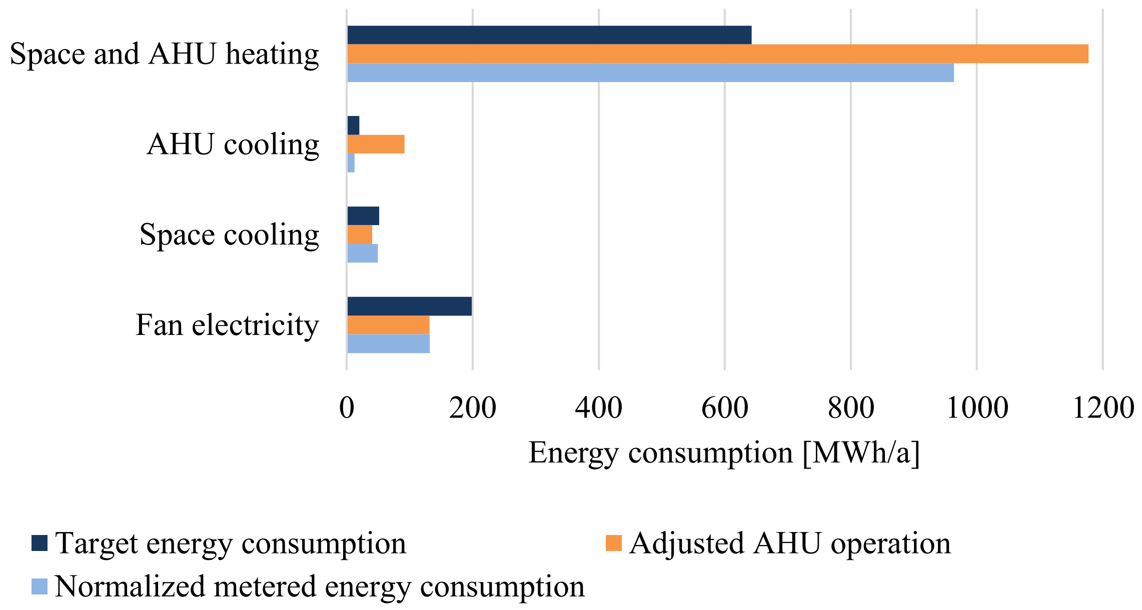

Figure 11. The relation of the energy consumption of the simulation with adjusted AHU operation schedules to the target energy consumption and metered energy consumption regarding the differing end-uses.

Ventilation air flows

Initially, space specific control dampers were designed to be applied in the office and conference rooms allowing demand control ventilation to be used. The air flows serving these spaces would be automatically adjusted within their range to provide the required indoor conditions. However, during the construction phase for economical saving purposes, more centralized dampers were installed resulting in a significantly lower adjustability of the supply air flows. Moreover, the control dampers are left to a constant position and since they lack remote controllability as well as metering of air flows or the damper positions, the actual position of the dampers cannot be identified.

With a constant positioning of the control dampers, the air flows to the spaces is constant in the actual building operation. The air flows of the spaces, where variable air flows were designed, are between the minimum and maximum allowed air flows. Since, the position of the dampers is unknown, the actual air flows to the spaces with initially designed demand control ventilation is unidentified. Therefore, the air flows of these AHUs need to be estimated.

To examine the effect of the substitution of the variable air flow systems with constant air flow systems, two different adjustments are simulated. Firstly, all spaces with variable air flows are modelled to be served with the constant initial minimum air flow. Secondly, the spaces are modelled with the minimum air flow and an additional air flow of 20 % from the maximum air flow. It should be noted however, that not all spaces are designed to have variable supply air flow and therefore, the estimated additional supply air flow is only calculated for spaces with demand control ventilation according to the design. The designed minimum and maximum air flows and the estimated air flow with a 20 %-addition to the minimum air flow by air handling units are presented in Table 7.

Table 7. The designed and estimated air flows of the air handling units.

	Designed minimum supply air flow L/s	**Designed maximum supply air flow L/s**	**Estimated supply air flow L/s**
301TK – 303 TK Offices	11199	18062	12572
304TK Kitchen	4052	7997	4841
305TK Restaurant	1542	2827	1799
306TK – 311TK Auxiliary spaces (CAV)	5020	5020	5020

The substitution of the variable air systems with constant air systems affects the space and supply air heating and cooling as well as fan electricity. The consumptions of these end-uses in both adjusted cases are presented in Figure 12. The other end-uses remain equal to the initial model. Heating, supply air cooling and fan electricity are decreased, when a CAV system with the minimum air flow is applied and increased, when an additional 20 % is added to the air flows.

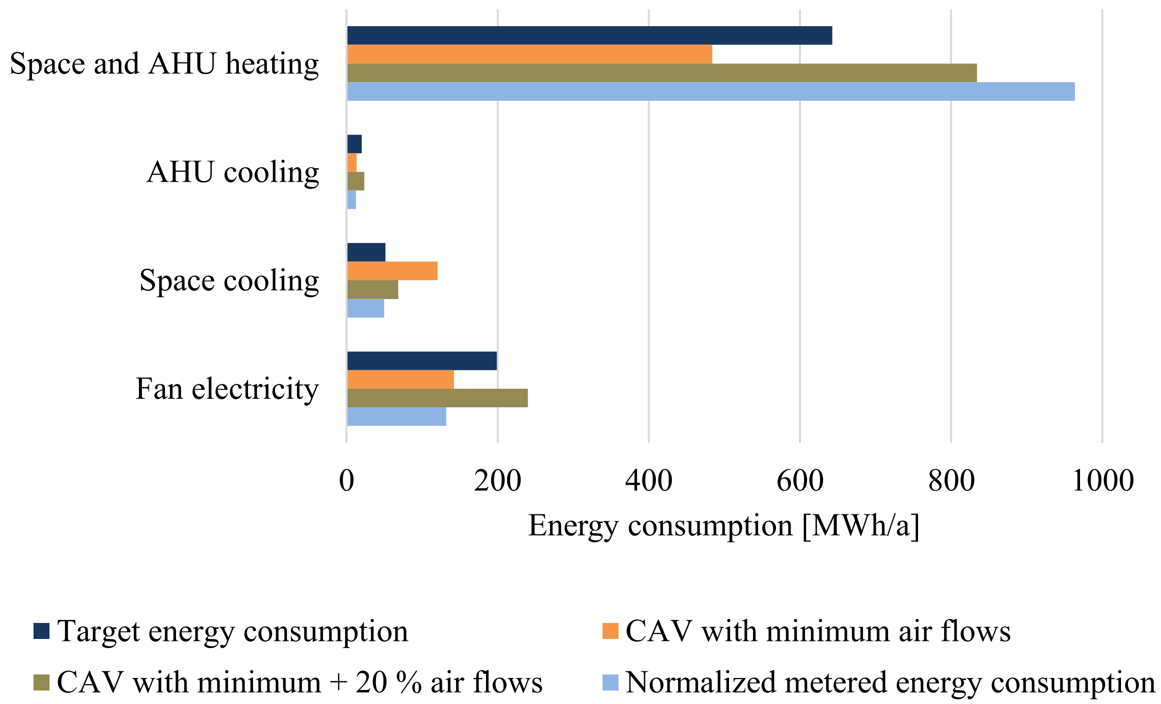

Figure 12. The relation of the energy consumption of the simulations with adjusted air flow rates to the target energy consumption and metered energy consumption regarding the affected end-uses.

In space heating, the adjusted simulation with estimated air flows provides the most accurate consumption when compared to the metered consumption. In AHU cooling and fan electricity, the simulation with constant minimum air flows results in most accurate results in comparison to the metered consumption. Space cooling is dependent of the amount of cooling demand covered by the supply air and therefore is increased with constant lower air flows than in the initial model and decreased with higher air flows in the second adjustment. Overall, the adjusted model with minimum air flows has a 18 % lower total energy consumption than the metered consumption, but the model with increased air flows exceeds the metered consumption by 1 %.

Supply air and indoor temperature setpoints

In the design documents, the indoor temperature setpoints of the office spaces, conference rooms, corridors and lobbies are defined as 21.5 °C for heating and 24.5 °C for cooling according to the IEQ class S1 of the Finnish building instructions (Rakennustietosäätiö RTS 2008). However, the actual heating setpoint for these spaces visible in the building operating system is on average 22.5 °C that is 1 °C higher than in the initial model. The cooling setpoints are rather equal in both the design and actual operation.

In addition to the indoor temperature setpoints, the supply air temperature setpoints and schedules vary significantly between the design and the building operating system. In most air handling units, the actual supply air temperature during extreme heating hours is higher than in the designed supply air temperature. During extreme cooling hours, the actual supply air temperature is lower, respectively. However, the outdoor temperature limits defining the supply air temperature are significantly higher in the actual operation than in the design document resulting in notably increased heating demand of supply air.

Moreover, during the cooling period, the supply air temperatures of the actual operation reach lower values in higher outdoor temperatures than in the design, resulting in a decreased cooling demand of supply air in the metered consumption. In AHUs 301TK – 307TK, the lowest supply air value is not reached until the outdoor temperature is 22 – 24 ˚C. Considering that the reference year 2012 has 281 hours with an outdoor temperature over 20 ˚C, but only 166 hours with an outdoor temperature over 22 ˚C and 73 hours with an outdoor temperature over 24 ˚C, the cooling hours of supply air are strongly reduced in the actual operation (The Finnish Environmental Institute 2011b).

In this case both the supply air temperature and the indoor temperature setpoints are corrected to the model allowing to see the effect of the temperature differences in the whole model. The designed and actual supply air temperature schedules of the air handling units are presented in appendix 4.

Adjusting the supply and indoor temperature setpoints results in a higher heating demand for supply air and lower heating demand for space heating. The increase in supply air heating is due to higher supply air temperatures, since the supply air temperature is purely dependable from the outdoor air temperature. The space heating consumption is reduced due to the increased share of the supply air heating from the total heating demand. However, the increased indoor heating setpoints result in a more moderate decrease of the space heating consumption.

Furthermore, with higher supply air temperatures, the supply air cooling consumption is reduced increasing the share of space cooling. Due to variable air volume systems, the significantly increased supply air heating demand increases the fan electricity consumption, even though the reduced supply air cooling slightly compensates the change. The relation of the adjusted model to the target energy consumption and metered consumption is presented in Figure 13 regarding all the end-uses differing from the initial model.

The space and supply air heating consumption of the adjusted model is higher than the target energy consumption, but lower than the metered consumption indicating a positive change towards an improved model. Additionally, the supply air cooling electricity consumption is relatively close to the metered one. On contrary, the space cooling and fan electricity consumptions have increased over both the target energy consumption and the metered consumption. The total energy consumption of the adjusted model is 4 % lower than the metered consumption.

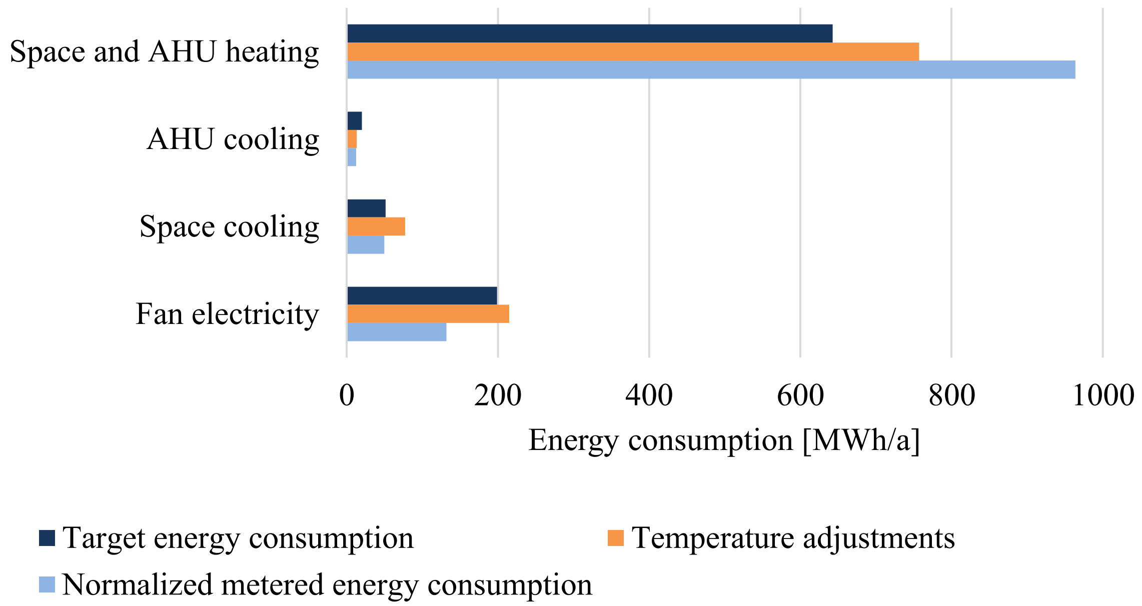

Figure 13. The relation of the energy consumption of the simulation with adjusted temperature setpoints to the target energy consumption and metered energy consumption regarding the affected end-uses.

Adjusted heat recovery efficiency

The heat recovery efficiencies of the air handling units are modelled according to the designed yearly average efficiencies of each unit. However, the actual yearly efficiencies vary depending on the system temperatures for the indoor and outdoor air as well as the air handling unit operation. As heating is one of the major end-uses also resulting for the highest gap, investigating the effect of the heat recovery efficiency adjustment provides relevant information regarding the gap formation.

The metered efficiencies during one year with a 5-minute time step are logged into the building automation for AHUs 301TK – 304TK. There is no logged data for the efficiencies of the other air handling units and the data from the AHU 304TK is calculated falsely in the building automation system not providing the needed information. Nevertheless, since the units 301TK – 303TK serving the office and conference rooms cover the majority of the building area and have the highest air flows, the accuracy of their heat recovery efficiencies has the greatest effect on the heat consumption regarding heat recovery adjustments.

The average yearly metered heat recovery temperature efficiency for the air handling units 301TK – 303TK and 305 TK is 69 %, notably lower than the designed efficiency of 80 %. The designed and metered yearly average heat recovery efficiencies for the air handling units are presented in Table 8. A new model is created based on the initial model with adjusted heat recovery efficiencies in the AHUs as metered. For the AHUs with no available information, the designed yearly heat recovery efficiency is used.

Table 8. The designed and actual heat recovery temperature efficiencies of the air handling units.

	Designed yearly HRU %	**Metered yearly HRU %**
301TK - 303TK Offices	80 %	69 %
304TK Kitchen	50 %	Unknown
305TK Restaurant	80 %	69 %
306TK – 307TK Restrooms	50 %	Unknown
308TK – 311TK Auxiliary spaces	-	-

Lowering the heat recovery unit efficiency of the office AHUs by 11 %-units results in a 58 MWh/a higher supply air heating consumption, but has no effect in the other end-uses. It should be noted, however, that should the HRU efficiency of the other AHUs be lower than designed as well, the difference is increased. The total energy consumption of the model is 8 % lower than the metered consumption.

Combined ventilation adjustments

To investigate the total effect of the studied mismatching factors regarding the air handling units, the adjustments explained in chapters for ventilation schedules, demand control ventilation, supply and indoor temperature setpoints and adjusted heat recovery efficiency are combined in one model representing the actual AHU operation of building as accurately as possible with the available information. From the air flow rate adjustments, the case with the minimum air flows with additional 20 % of the difference between maximum and minimum air flows is added, is chosen as most accurate for the studied building.

The major impact of the combined adjustments in ventilation is an increase of space and supply air heating by 41 % compared to the initial model to 56 MWh/a less than the normalized metered consumption. Additionally, the fan electricity consumption of the model is decreased by 36 % that is 4 % lower than the metered consumption. The adjusted model results in higher supply air and space cooling electricity consumptions than both the initial model and the metered consumption. Similarly to the individual adjustments combined, the other end-uses are not affected.

The adjusted model predicts a 3 % higher consumption than anticipated, thus being significantly more accurate than the initial model. The relation of the model with all the combined adjustments, the target energy and the metered regarding all the affected end-uses is presented in Figure 14.

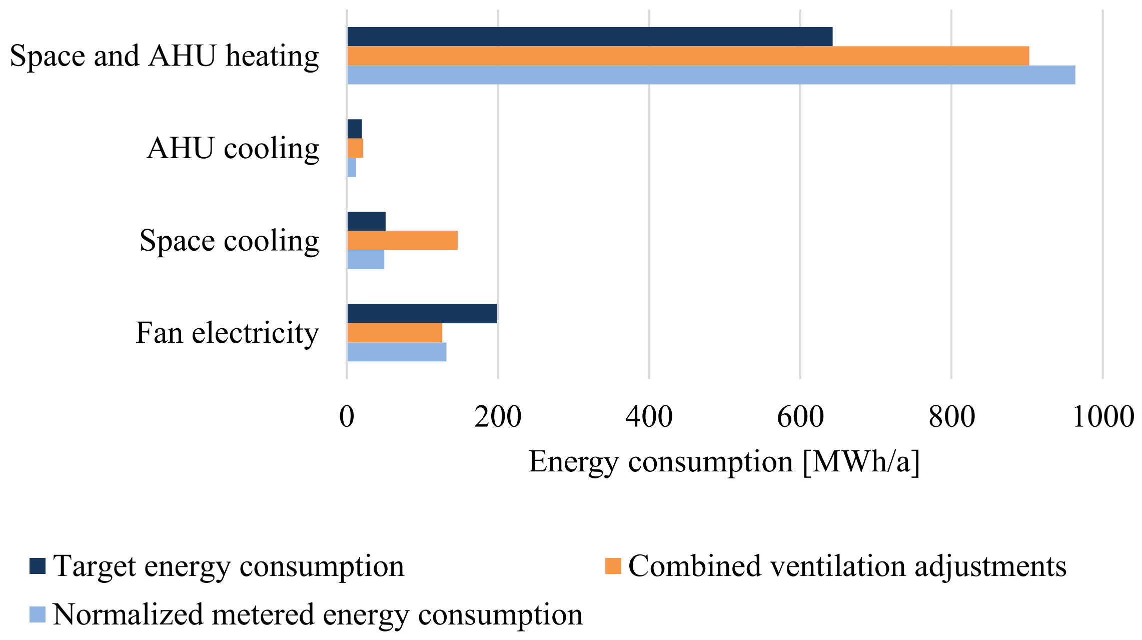

Figure 14. The relation of the energy consumption of the simulation with adjusted ventilation operation to the target energy consumption and metered energy consumption regarding the affected end-uses.

5.4.2 Building occupancy and use

Occupancy rate

The initial model is created for the building with full occupancy in all tenant spaces considering the variation in occupancy schedules. However, the highest floor of the case building has had no tenants during the studied year. This is accounted in an adjusted model by removing all occupant, lighting and receptacle equipment loads from the tenant spaces of the highest floor. The lighting loads of public spaces, such as stairways, technical spaces and storage rooms are not changed, since they are used also when the tenant spaces are not in use. In practice the occupancy of such auxiliary spaces might be reduced due to the partial occupancy, but the effect of the reduction is assumed insignificant and is therefore not considered.

The partial occupancy reduces the tenant lighting and equipment electricity consumption as expected, without affecting the facility lighting and equipment electricity. Additionally, it increases the space heating demand and reduces supply air and space cooling as well as fan electricity consumption. The consumptions of the end-uses differing from the initial model are presented in Figure 15 in relation to the sub-consumptions of the target energy consumption and the metered consumption.

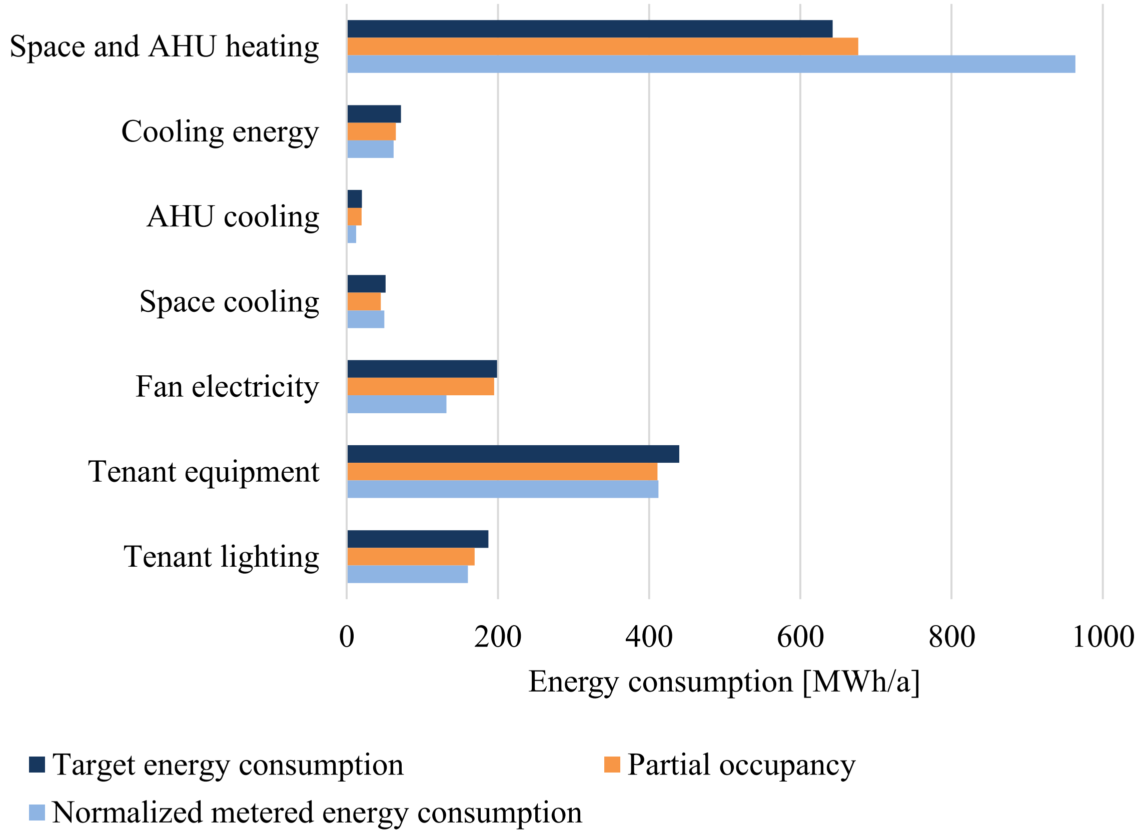

Figure 15. The relation of the energy consumption of the adjusted model with partial occupancy to the target energy consumption and metered energy consumption regarding the affected end-uses.

Regarding the occupant equipment and lighting consumption, the adjusted model is highly correlating with the metered consumption. Furthermore, the equipment electricity consumption of tenant spaces is accurately estimated, when partial occupancy is considered. Nevertheless, the space and supply air cooling electricity consumption is significantly lower than metered, even though the difference is lower than in the target energy consumption. The total cooling electricity consumption of the adjusted model is only 5 % higher than in the metered cooling electricity consumption. However, the share of AHU cooling is estimated greater resulting in a lower share of the space cooling. In total, the adjusted model has a 12 % lower consumption than metered.

Occupancy density

When surveyed the building owner of the occupancy level during the studied period, exact occupancy dates of different tenant spaces are obtained. Without consideration of the partial occupancy, the average space area required by each occupant in office spaces and conference rooms is 5.5 m^2/person, while the estimated area is 14 – 16 m^2/person. Thus, the estimated occupancy density is almost three times higher than the actual density.

With an increased occupancy density and resulting increased internal heat gains, the space and supply air heating consumption of the adjusted model is reduced, while the space cooling is increased. The slightly reduced supply air heating demand reduces also the fan electricity consumption in the variable air volume systems. Other end-uses are not affected by the adjustment. The consumption of the end-uses differing from the initial model are presented in Figure 16.

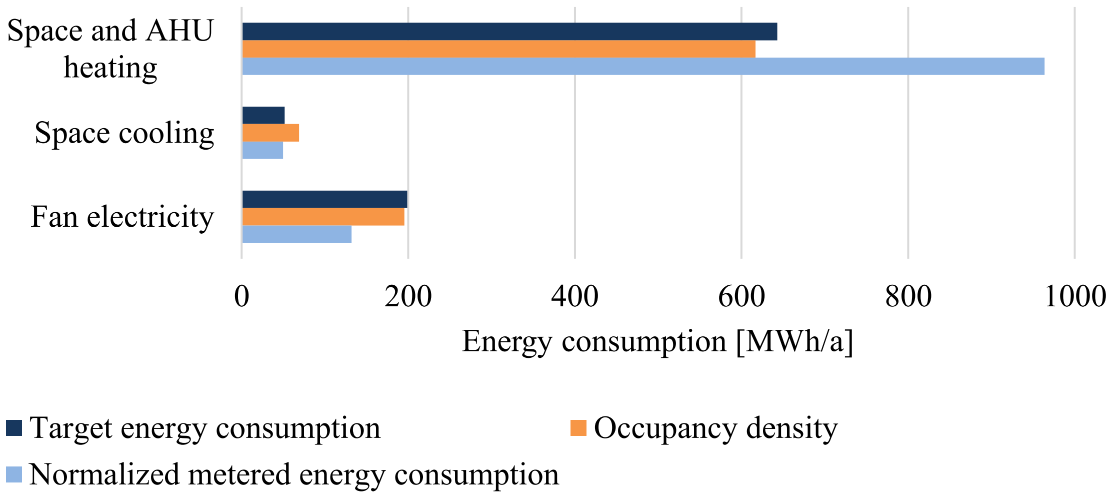

Figure 16. The relation of the energy consumption of the simulation with adjusted partial occupancy to the target energy consumption and metered energy consumption regarding the affected end-uses.

Compared to the metered consumptions, space and supply air heating are highly underestimated, whereas space cooling and fan electricity are overestimated. The total impact of the change in occupancy density is nearly insignificant, considering that it results in less than 1 % change to the target energy consumption. However, it is one explaining factor in the mismatch between the metered and the target energy consumption regarding heating, cooling and fan electricity. The adjusted model has a 12 % lower total energy consumption than metered.

Lighting schedules

When partial occupancy is considered in the model, the lighting electricity consumption of tenant spaces is 5 % overestimated. The slight overestimation of the lighting electricity consumption in the tenant spaces can be explained by occasional differences in the lighting schedules resulting from holiday absences or other unregular events, and the lighting power density and main schedules can be assumed to be relatively correct. The anticipated average lighting power density in tenant spaces is 10.4 W/m^2. Lighting electricity in facility use is however 48 % underestimated both in the target energy consumption and the model with adjusted partial occupancy. Thus, the schedules for facility lighting are suggested to be incorrect.

In the initial model, the main schedules for facility lighting, are assumed to be from 8 am to 5 pm on the weekdays and all the other time, the lighting is assumed to be off, as it would be in an ideal situation. However, when the hourly logged data of the building is examined under the sub-consumption for facility electricity, a significant 7 kW base load is observed during non-occupied hours. Accordingly, the facility lighting operation during occupied hours is on average only 70 % from the maximal lighting power. The estimated and observed main schedules for facility lighting are presented in Figures 17 and 18. The estimated operating schedule is 45.0 h/week at full load operation whereas the observed operating schedule is 44.6 h/week at full load operation. Thus, there is merely no difference in interior facility lighting electricity consumption.

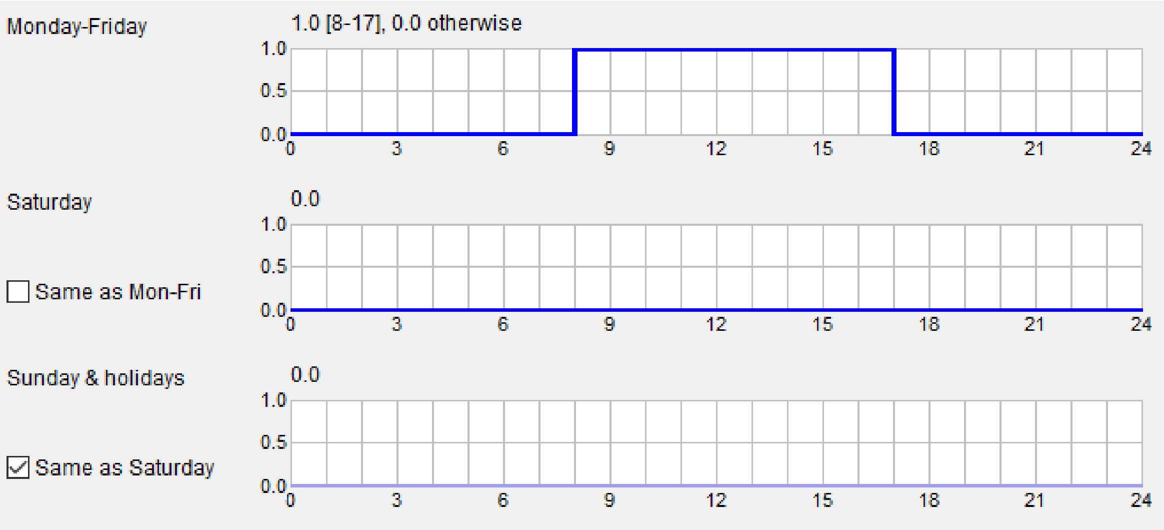

Figure 17. The estimated operating schedule for facility lighting.

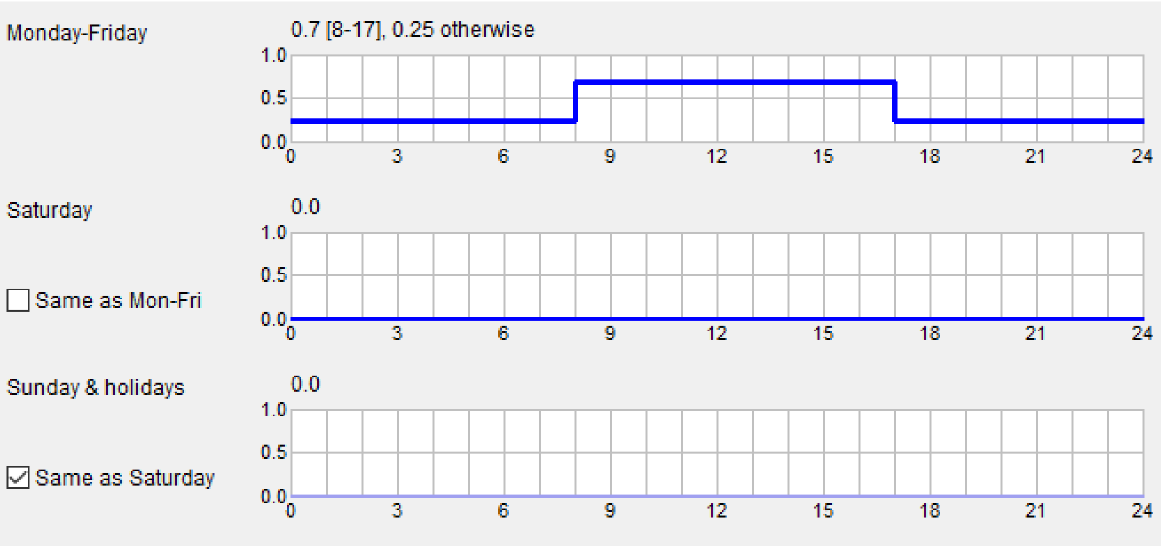

Figure 18. The observed operating schedule for facility lighting.

Moreover, on contrary to the assumptions, the majority of the exterior lighting operates continuously throughout the year instead of turning off during hours with high natural luminance levels. This can be explained by continuously operating advertisement lighting in the exterior facades, malfunctioning lighting sensors or incorrectly predefined automatic operation of exterior lighting ignoring the installed lighting sensors. Several factors can also act together. Therefore, difference in exterior lighting operation contributes to nearly all the gap between the metered and the estimated facility lighting consumption. Both the interior and exterior lighting schedules are adjusted in a new model and a new simulation is performed.

Due to increased interior facility lighting operation during morning and evening hours, the interior heat gains during this period are increased reducing the need for space heating. Consequently, the total heating consumption is reduced and space cooling is slightly increased. However, fan electricity is not affected since the increased lighting operation is applied only in facility spaces with no demand control ventilation. The changes in the affected end-uses are presented in Figure 19.

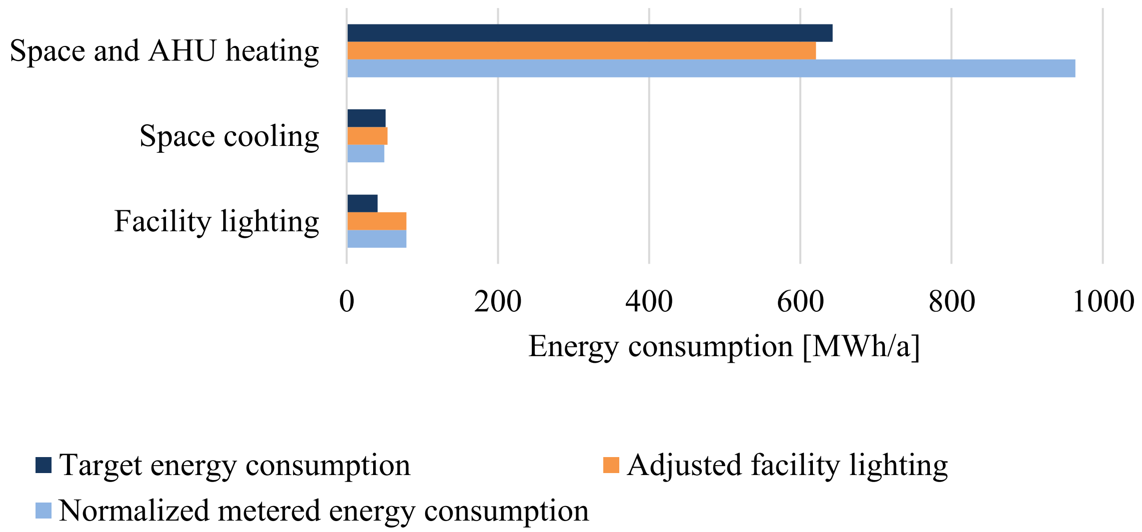

Figure 19. The relation of the energy consumption of the model with adjusted facility lighting to the target energy consumption and metered energy consumption regarding the affected end-uses.

The electricity consumption of facility lighting in the adjusted model is at the same level as the metered consumption. However, the changes in heating and cooling are not positive towards the metered consumptions. Nevertheless, they reflect the changes occurring from the increased facility lighting operation and can be used together with other adjusted factors in creating a more accurate model. The total energy consumption of the adjusted model is 10 % lower than the metered consumption.

Equipment power density

Since the tenant receptacle equipment electricity consumption of the model with adjusted partial occupancy represents quite accurately the metered tenant equipment electricity consumption, the equipment power density and operating schedules are assumed to be correct with the anticipated average equipment power density of 26.6 W/m^2 in tenant spaces. However, the electricity consumption of facility equipment is modelled 36 % lower than the metered consumption.

The electricity consumption of lifts and de-icing network are relatively correctly estimated, but the electricity consumption of auxiliary building automation systems such as safety, fire protection, access control, cleaning electricity, entry systems and burglary and handicapped restroom alarms as well as additional electricity for cooling and losses in technical spaces were underestimated. Such auxiliary systems consume 83 MWh/a in the case building, which equals 5.4 kWh/m^2/a.

Since the electricity consumption of facility equipment is treated as additional electricity consumption in the models and considering all losses in the value, the adjustment of the facility equipment electricity consumption does not affect other end-uses in the building, even though in the actual building the effects would be visible. By correcting exclusively the equipment power, the total energy consumption compared to the metered consumption is 9 % lower.

Domestic hot water use

In addition to the number of occupants, lighting and equipment use, the occupancy levels of the building reflect also the domestic hot water consumption. Initially, the estimate for heating demand of domestic hot water was calculated according to the building type and area dependent value defined as 6 kWh/m^2,a for office buildings in the Finnish Building Code section D3. The estimate is known to be a weak estimate as it does not consider the occupancy density, but as the exact density is unknow during the design phase, this estimate is used to roughly predict the magnitude of DHW heating demand.

Since the metered DHW heating consumption is 3.3 kWh/m^2,a, the metered DHW heating consumption is 58 % lower than the estimated consumption. Hence, the partial occupancy cannot fully explain the overestimated hot water consumption and the used estimate from the Finnish Building Code does can be considered as a poor estimate not describing the actual consumption correctly in the studied building. It should be noted however that the building is LEED certified and has therefore water fixtures with low water consumption.

According to Motiva Oy (2016), a typical hot water use by dishwashing in a catering space is 2.5 L/portion. Since the actual number of full-time occupants is known to be 410 persons and assuming 80 % - 100 % of the occupants dine once each working day, the annual DHW consumption by dishwashing can be estimated to vary from 211 m^3/a to 263 m^3/a. The DHW heating demand required for dish washing can be calculated with equation 2, where $Q_{DHW,dw}$ [kWh/a] and $V_{DHW,dw}$ [m^3/a] are the heating demand and volume flow of DHW consumed by dish washing, ρ_w [kg/m^3] and c_{pw} [kJ/kgK] are the density and heat capacity of water and ΔT_w [°C] is the temperature difference between hot and cold domestic water, which is assumed to be 50 °C (The Finnish environmental institute 2012c). Thus, the annual heating demand for DHW used for dish washing in the studied building can be approximated from 12.6 MWh/a to 15.8 MWh/a.

$$Q_{DHW,dw} = \rho_w c_{pw} V_{DHW,dw} \Delta T_w \tag{2}$$

Assuming, the estimate for DHW used for dish washing is appropriate, the full-time occupants are responsible for the remaining 586 m^3/a - 638 m^3/a calculated according to equation 2. This signifies that the actual DHW heating consumption by occupancy in the studied building varies from 1.4 m^3/person,a to 1.9 m^3/person,a contributing to 85.7 kWh/person, a to 116.8 kWh/person, a.

Adjusting the DHW demand in the model affects the space heating demand, since heat losses from hot water into spaces decrease the need for space heating. As the DHW demand is decreased, a slight increase in the space and supply air heating can be observed. The changes in the affected end-uses are presented in Figure 20. The total energy consumption of the adjusted model is 14 % lower than the metered consumption.

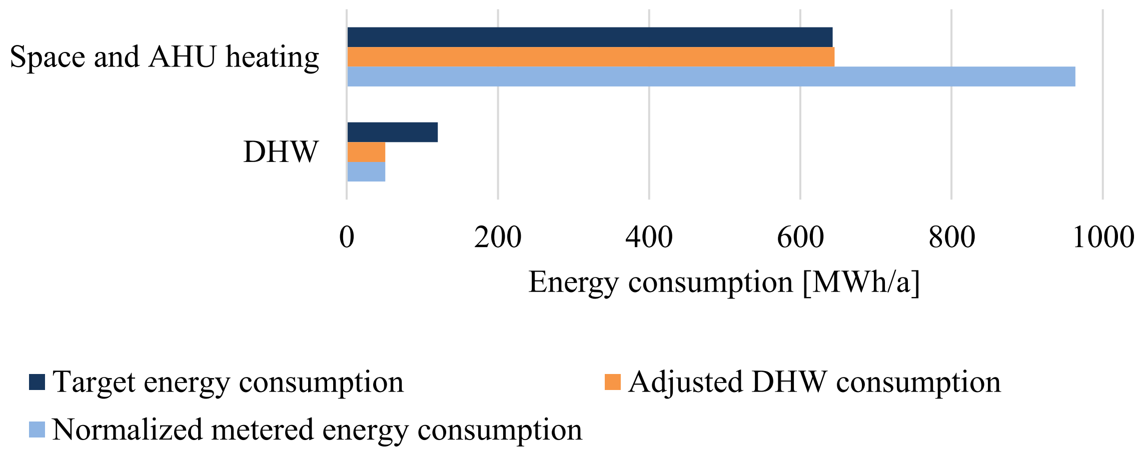

Figure 20. The relation of the energy consumption of the simulation with adjusted domestic hot water use to the target energy consumption and metered energy consumption regarding the affected end-uses.

Combined occupancy and use adjustments

In order to study the combined effect of adjusted internal loads, a model is created considering the adjustments explained in chapters for partial occupancy, occupancy density, lighting schedules, equipment power density and domestic hot water use. As in the separate adjustments of facility lighting and equipment, in the improved model these consumptions represent correctly the metered consumptions. The tenant lighting and equipment consumptions of the improved model are equal to the consumptions of the case investigating solely the effect of partial occupancy of the building.

Compared to the initial model, the increase in facility lighting is slightly lower than the decrease in tenant equipment and lighting consumptions indicating, that the total internal heat gains from lighting and receptacle equipment decrease. However, since the occupancy density in the tenant spaces is higher than in the initial model, the total internal loads increase by 22 MWh. Consequently, the heating demand slightly decreases and the cooling demand slightly increases. This indicates that the schedule of the internal heat gains correlates with the hours of high heating and cooling demand. Additionally, the occupancy density has the strongest effect in the change of internal heat gains as it allows the total heat gains to rise despite the lowered lighting and equipment consumption. The heat load from occupants covers 33 % of the total internal heat loads in the target energy consumption model.

The fan electricity consumption is decreased contrary to the general heating and cooling. This is due to a slight reduction in supply air cooling resulting from lower indoor temperatures in the unoccupied floor. The decrease of supply air cooling in the highest floor indicates also a reduced demand control ventilation resulting in a lower fan operation and electricity consumption. The heating consumption of DHW corresponds with the metered consumption after the adjustment.

When all internal loads and schedules for lighting, receptacle equipment and occupancy are adjusted, the performance gap is reduced by 1 %-unit with the total metered consumption being 12 % higher than the consumption in the improved model. Nevertheless, the differences in heating and cooling consumptions are still significant. The changes in all relevant end-uses in the improved model are presented in Figure 21, while other end-uses are not affected by the adjustments.

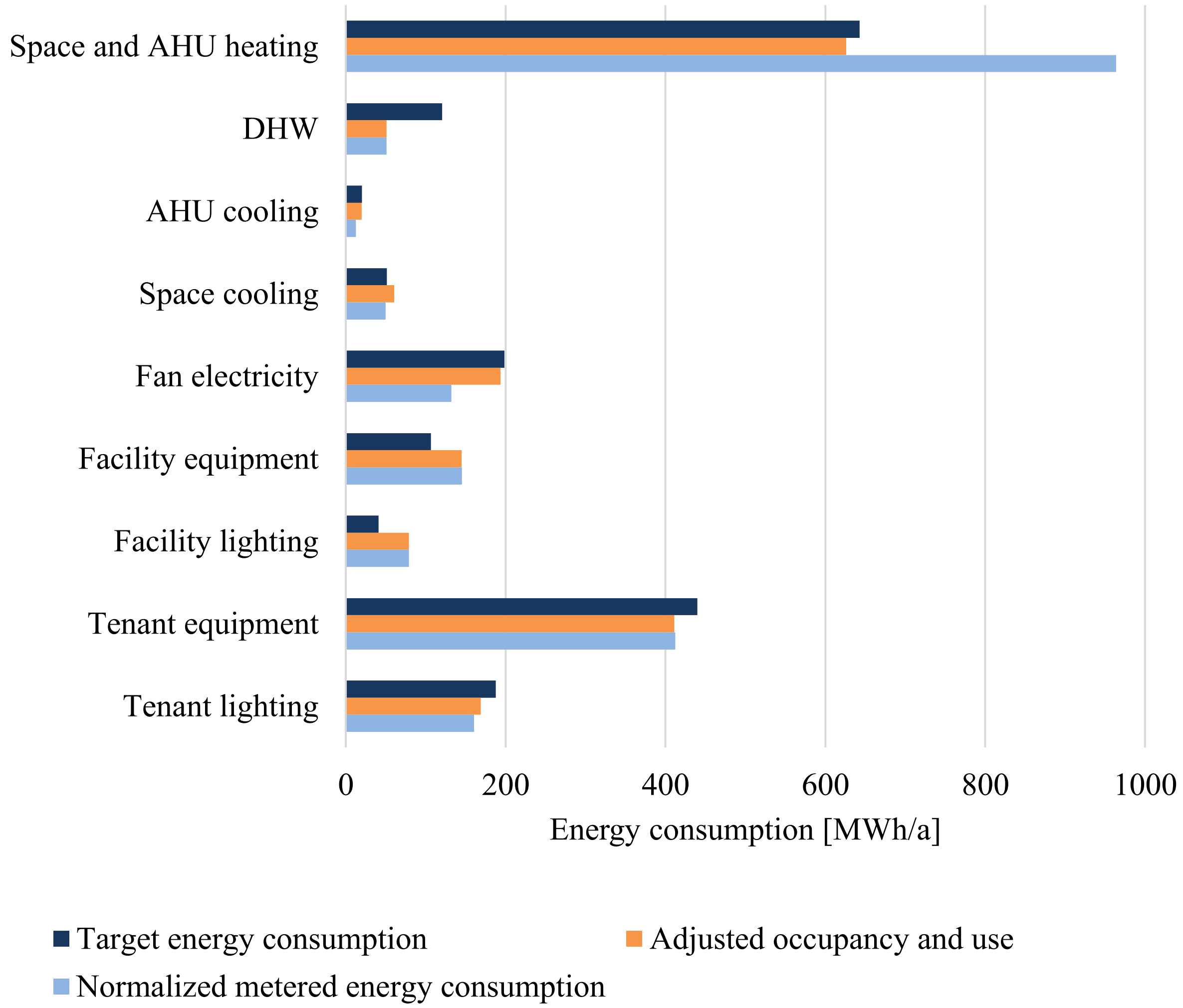

Figure 21. The relation of the energy consumption of the simulation with adjusted occupancy and use to the target energy consumption and metered energy consumption regarding the affected end-uses.

5.4.3 Heating and cooling systems

Heating distribution method

In the initial model, the heat distribution method is only considered in calculation of losses from space heating, and the distribution components were not modelled space specifically. The heating and cooling distribution is thus modelled with ideal heaters and coolers. However, to investigate the effect of the heat distribution method to the heating and cooling consumption, the relevant heat exchanging components are added to the model into each space.

When supply air is not considered, the main heating and cooling distribution system in the studied building are radiant ceiling panels providing heating and cooling of the space. In the ground floor, the heating system applied is floor heating. The supply and return water temperatures of the radiant ceiling panels during heating are 45 °C and 30 °C, respectively. Accordingly, in floor heating the supply and return water temperatures are 40 °C and 30 °C. The heating systems of the auxiliary spaces are not modelled as such spaces are typically located in central zones requiring less heating and cooling, and therefore have an insignificant effect on the total heating energy demand.

Adding the heat distribution components into the spaces slightly increases the heating consumption and supply air cooling, whereas the space cooling is significantly reduced. Along with increased supply air cooling, the fan electricity consumption is slightly increased. The total energy consumption of the improved model is 11 % lower than the metered consumption. The differing end-uses are presented in Figure 22.

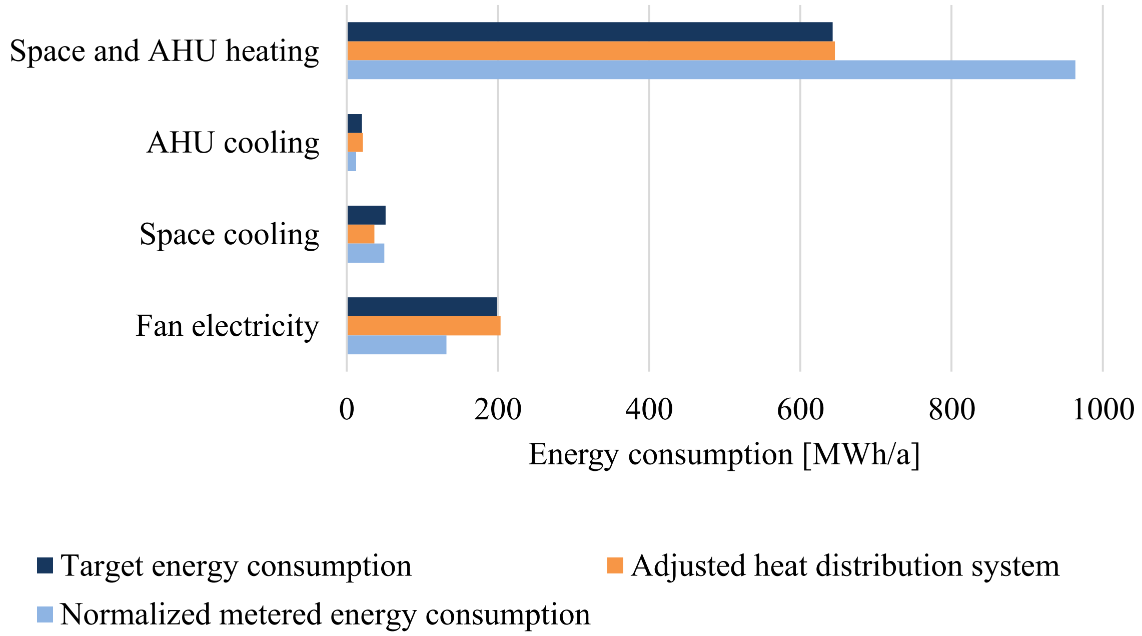

Figure 22. The relation of the energy consumption of the improved model to the target energy consumption and metered energy consumption regarding the affected end-uses.

Cooling network pumps

In the initial model, the pump electricity consumption consisting of heating and cooling pump electricity is 36 % lower than metered. Furthermore, the cooling pump consumption is 35 % underestimated while the heating pump consumption estimate is rather accurate. Therefore, the monthly metered and simulated cooling pump operations are compared, and relevant errors are observed in the model.

During the heating season, the simulated cooling pump electricity consumption is zero, while the metered consumption is rather constant with a base load of 4 kW. Thus, unlike supposed, the cooling pumps operate at a constant power of 38 % from their nominal capacity even when no cooling is needed. However, during the cooling season, the simulated cooling pump operation is notable, but lower than the metered consumption. Especially during May, June and September, the simulated consumption remains significantly below the metered level.

An improved model is created with setting the actual maximal cooling capacity and flow of the fluid defined in the design documentation. Additionally, the cooling system operation type is changed from unlimited to polynomial riding the pump curve. From January to May and from September to December, while the simulated consumption is low or zero, the metered base load is added into the improved model. The distribution of the cooling pump electricity consumption of the initial and improved models as well as the metered consumption are presented in Figure 23.

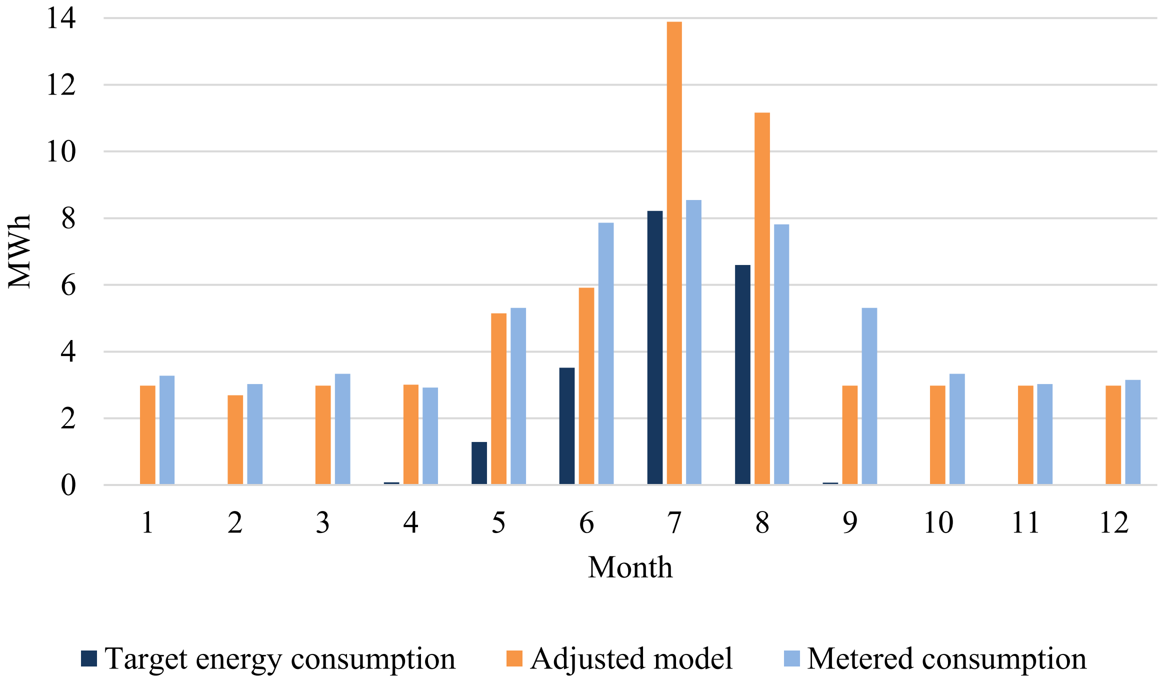

Figure 23. The relation of the monthly cooling pump electricity consumption of the improved model, the target energy consumption and metered energy consumption.

The improved model shows a more accurate monthly distribution of the cooling pump consumption than the initial model. However, the simulated consumption of July and August are significantly overestimated, while June and September are underestimated. This is possible due to yearly varying outdoor temperatures, which are only considered in normalization of heating, while cooling is not accounted. Likewise, reduced operation during summer and changes in the AHU operation or indoor temperatures may affect the monthly distribution of cooling pump operation.

It should be noted as well that the changes in pump electricity consumption are not visible in other adjusted cases due to the assumption for optimal pump and cooling operation by the model. Interestingly, adjusting the cooling system technical details does not affect the cooling consumption, but solely the pump electricity consumption. In the improved model, the total pump electricity consumption exceeds the metered consumption by 1 % while the total energy consumption is 9 % lower.

5.5 Improved input data

To observe the total impact of the studied adjustments, an improved model is created including both the ventilation, occupancy and use related adjustments presented in Chapters 5.4.1 and 5.4.2. Additionally, the cooling pump operation and heat distribution method are included in the model as explained in Chapter 5.4.3. Consequently, the model has only 1 % higher total energy consumption than metered. Furthermore, difference in heating electricity is reduced from 33 % to 6 % and the difference in general electricity consumption is reduced from 1 % to 0 %. However, the difference in cooling is increased from 15 % to 118 % but due to its low magnitude, its effect on the overall gap is minor.

As in the previous model with combined occupancy and use adjustments, the facility and tenant equipment and lighting as well as DHW heating correspond closely to the metered consumption. Likewise, as in the previous model with combined ventilation adjustments, the fan electricity and supply air cooling as well as the overall heating consumption are close to the metered consumptions. Nevertheless, minor differences are present in these end-uses as seen in Figure 24. The major mismatching end-use is space cooling, as it is 129 % higher than metered.

As cooling is greatly overpredicted by the improved model, while heating and electricity consumption are relatively accurate, cooling contributes to the highest share of the remaining gap by 53 %. The share of each energy type in the remaining gap is presented in Figure 25. As the difference between the consumption prediction of the improved model and the metered consumption is low and the gap in all end uses except cooling electricity is reduced, the major mismatching factors are accounted in the final model. Additionally, the assumed higher air flows have likely the correct magnitude. The remaining gap is due to factors not included in the study as they have a minor impact on the gap. Furthermore, a gap can result from malfunctioning or improper use and maintenance of technical systems of the building. However, identification of such factors requires a further inspection of the building operation and is therefore not included in this study.

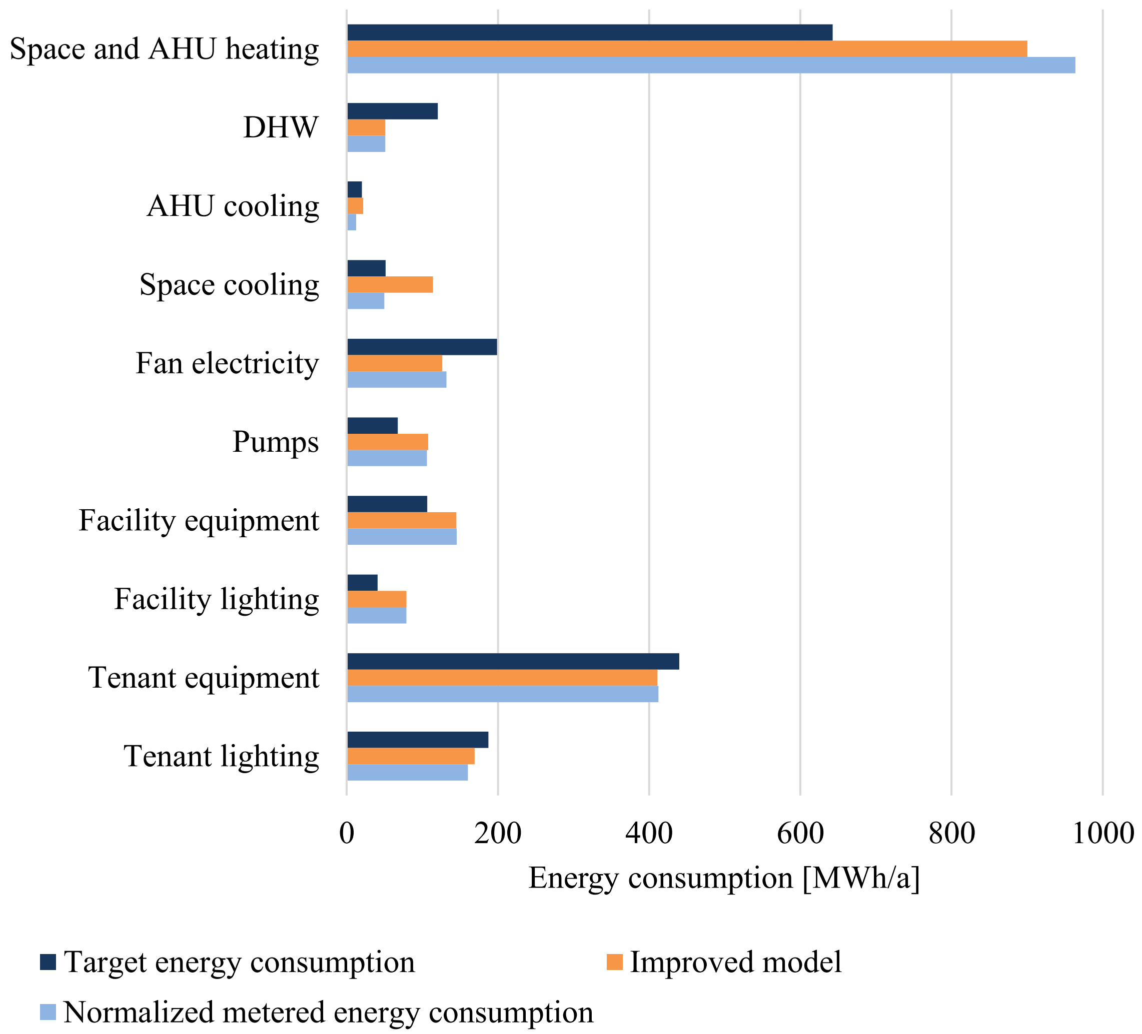

Figure 24. The relation of the energy consumption of the improved model to the target energy consumption and metered energy consumption by end-use.

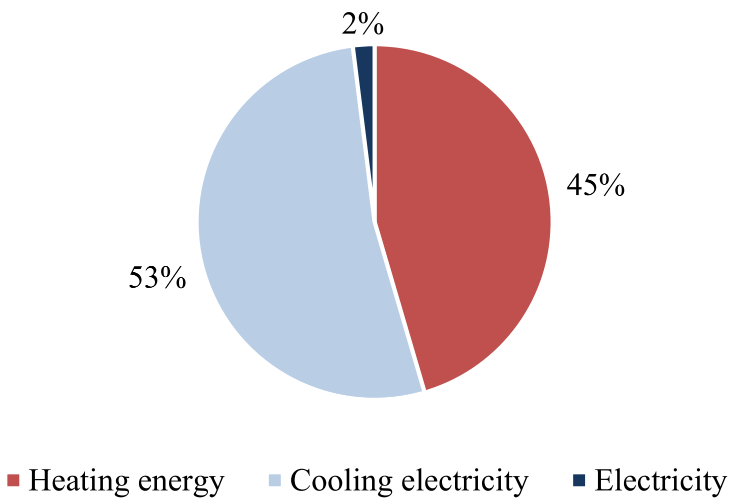

Figure 25. The share of the heating, cooling and other electricity consumptions in remaining gap.

6 Findings

6.1 Magnitude of the performance gap

The performance gap of the performed case study of an office building in Helsinki is 13 %, while the gaps in heating, cooling and electricity are 33 %, -13 % and -1 %, respectively. Despite the rather accurate general electricity consumption estimate, an explicit study of the metered end-uses reveals significant mismatches between the estimates and the metered consumptions both in electricity and heating end-uses. The difference of each estimated and metered sub-consumption is presented in Figure 26. Domestic hot water heating, supply air cooling and fan electricity are significantly overestimated while facility lighting and equipment electricity, pump electricity as well as space and supply air heating are significantly underestimated. All other end-uses differ by less than 20 %.

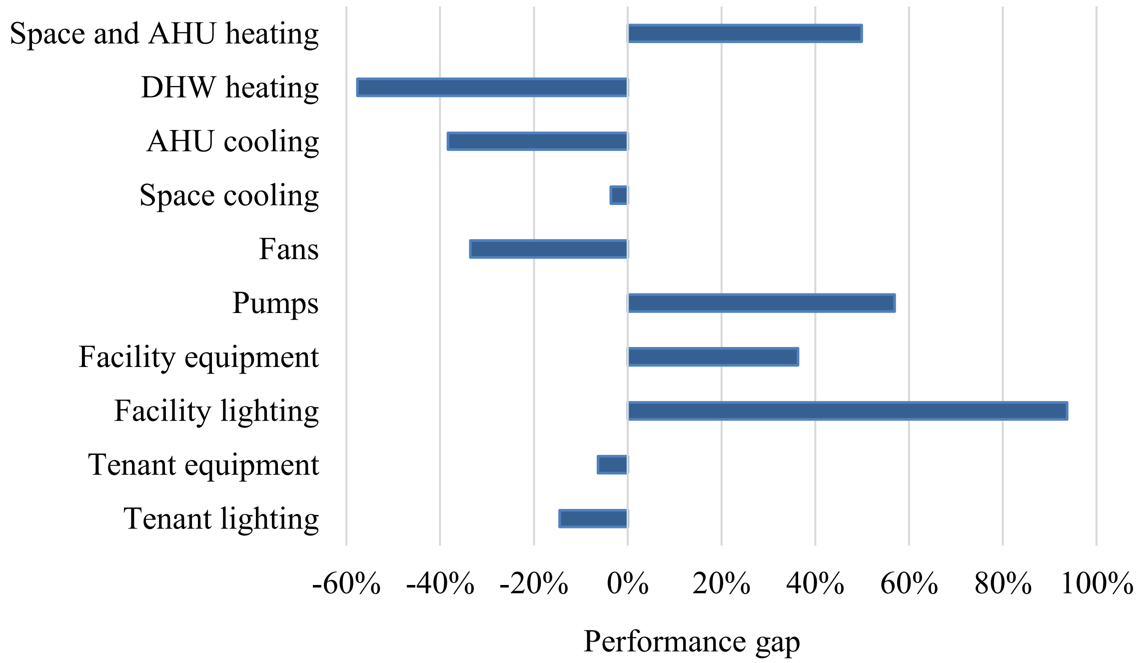

Figure 26. The relative difference of the target initial energy consumption and the normalized metered consumption by each metered end-use.

In addition to the annual comparison, there are differences also in a monthly level as visualized in Figure 9. The greatest mismatch is during the heating period from October to April, when the difference in heating is emphasized. Accordingly, the lowest mismatch is during the cooling period from May to September, when heating is low. The heating consumption of the building exceeds the estimates, since the AHU operation is mainly longer with high constant air flow rates and lower heat recovery efficiency during the heating period. Furthermore, cooling slightly exceeds the estimate due to the relinquishing of night time fan operation. Cooling is rather accurately modeled during the heating period, whereas it is overpredicted during the cooling period. However, due to the magnitude of cooling electricity consumption in relation to heating consumption, cooling electricity has little effect on the gap.

The general electricity consumption is rather constant on a monthly level considering ventilation, equipment and lighting electricity. Furthermore, ventilation electricity is slightly

increased during the cooling period due to the increased cooling pump and fan operation. Despite the differences in each sub-consumption in nearly each month, both the simulated model and the metered consumption show a similar monthly distribution with higher consumption during winter and lower during summer.
Based on the observed differences between the initial model and the actual building operation, an improved model is created with all the adjustments considered in the extent of the available information. The limitations in sub-metering, documentation and building automation data logging subject the improved model to mismatches with the actual building operation. Nevertheless, the total energy consumption of the improved model differs from the metered consumption by 13 MWh/a, which is 95 % less than the difference in the initial target energy consumption model.

Furthermore, the total gap is reduced from 13 % to 1 % in the improved model. The gap of each end-use is presented in Figure 27, while it can be noted that the gap in all end-uses except AHU and space cooling is reduced, and in DHW heating, facility and tenant equipment and facility lighting the gap is close to zero. Thus, the accuracy of the improved model is significantly higher than in the initial model in the studied yearly level.

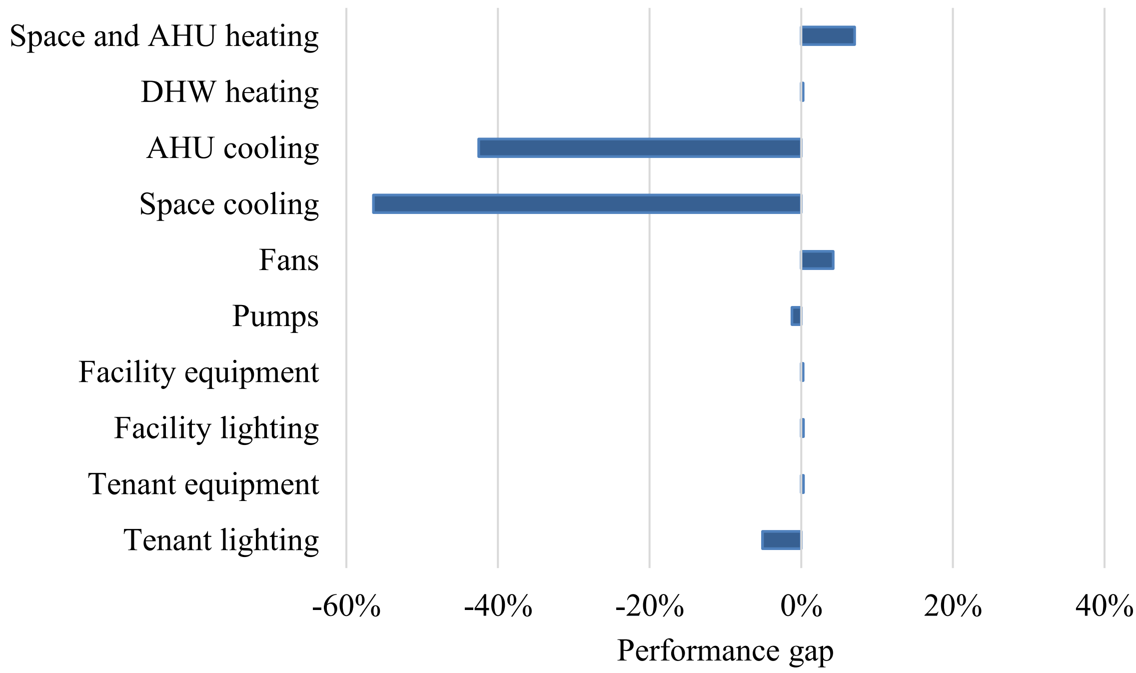

Figure 27. The difference of the energy consumption of the improved model with all measures combined and the normalized metered consumption by each metered end-use.

6.2 Major error causing parameters

6.2.1 Significance of the studied parameters

In this study, the effect of 15 measures is analyzed in the case building including an improved model with all available information corrected to the initial model. The investigated differences between the created model and the anticipated building operation include ventilation schedules, HRU efficiency, air flow and temperatures adjustments as well as occupancy, lighting, plug load and DHW adjustments. Additionally, the effect of precise modeling of the heat distribution method and cooling pumps operation are examined.

The effect of each adjustment on the total difference of energy consumption and on the difference of each energy type are summarized in Figures 28 , 29 and 30. The most accurate total energy consumption estimate is given with the adjustment of air flows of spaces designed with variable air flow systems but operating with constant air flows. It predicts heating consumption only 60 MWh/a lower, while the initial model predicts heating 250 MWh/a lower. The adjustment of indoor and supply air temperature setpoints and schedules provides the secondly most accurate prediction of the total energy consumption by underestimating the heating production by 137 MWh/a.

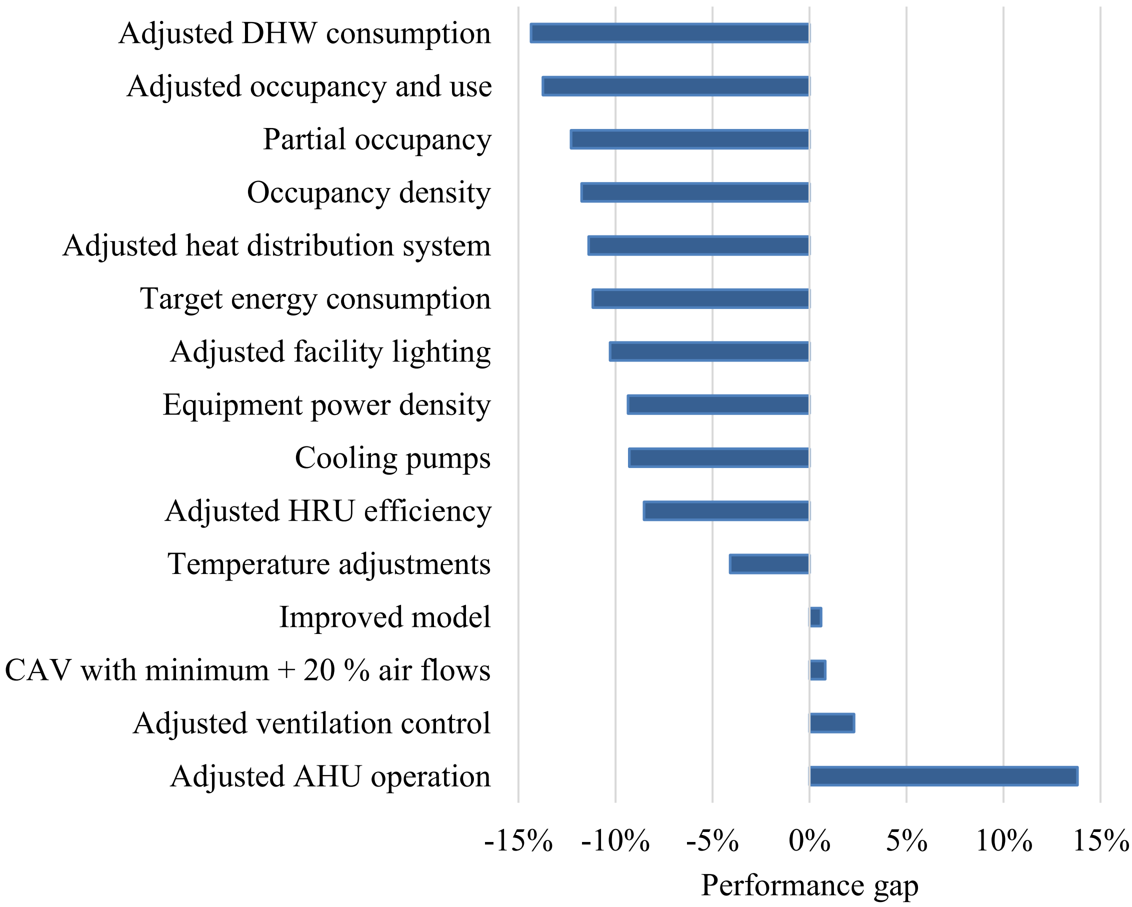

Figure 28. The total performance gap of each adjusted model.

The adjustments of the operating schedules of the AHUs have the most significant difference in the prediction of the total energy consumption with a difference of 528 MWh/a resulting in a significant overestimation of the energy consumption. Adjusting the operating schedules of AHUs has thus also the greatest effect of 224 % on the general performance gap. Additionally, air flow and temperature adjustments have a 107 % and a 63 % difference in the gap, respectively. HRU efficiency, cooling pump operation, equipment power density and DHW consumption have a notable but relatively lower impact on the gap while other adjustments are nearly insignificant. The combination of all ventilation related adjustments affects the gap by 123 %, notably more than the combination of occupancy and use adjustments, which increase the gap by 23 %.

However, while most adjustments reduce the total consumption estimates, the AHU operation schedules and air flow adjustments increase the estimates thus compensating the reduction of the other adjustments. The improved model provides the most accurate estimates as it includes all ventilation related adjustments as well as occupancy and use, heat distribution method and cooling pump adjustments.

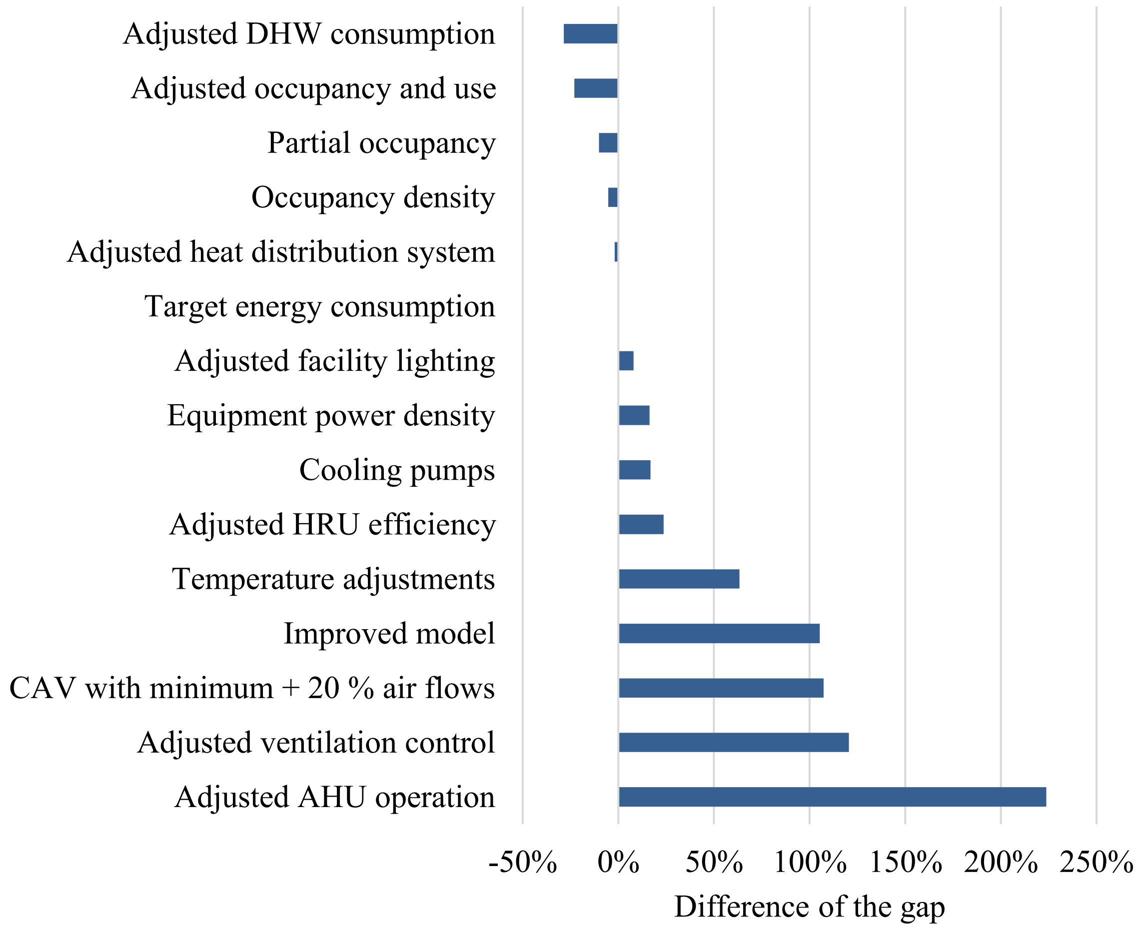

Figure 29. The effect of each adjustment on the total energy performance gap between the initial model and the metered consumption.

When all adjustments are considered, the gap is reduced from 13 % to 1 % reflecting somewhat accurately the anticipated consumption of the studied building. Moreover, considering all the studied factors for the mismatch, the final improved model shows a relatively accurate prediction of most end-uses while some end uses have approximately 0 difference with the metered consumption. The major differing end use in the improved model is space cooling with a 129 % higher consumption than metered.

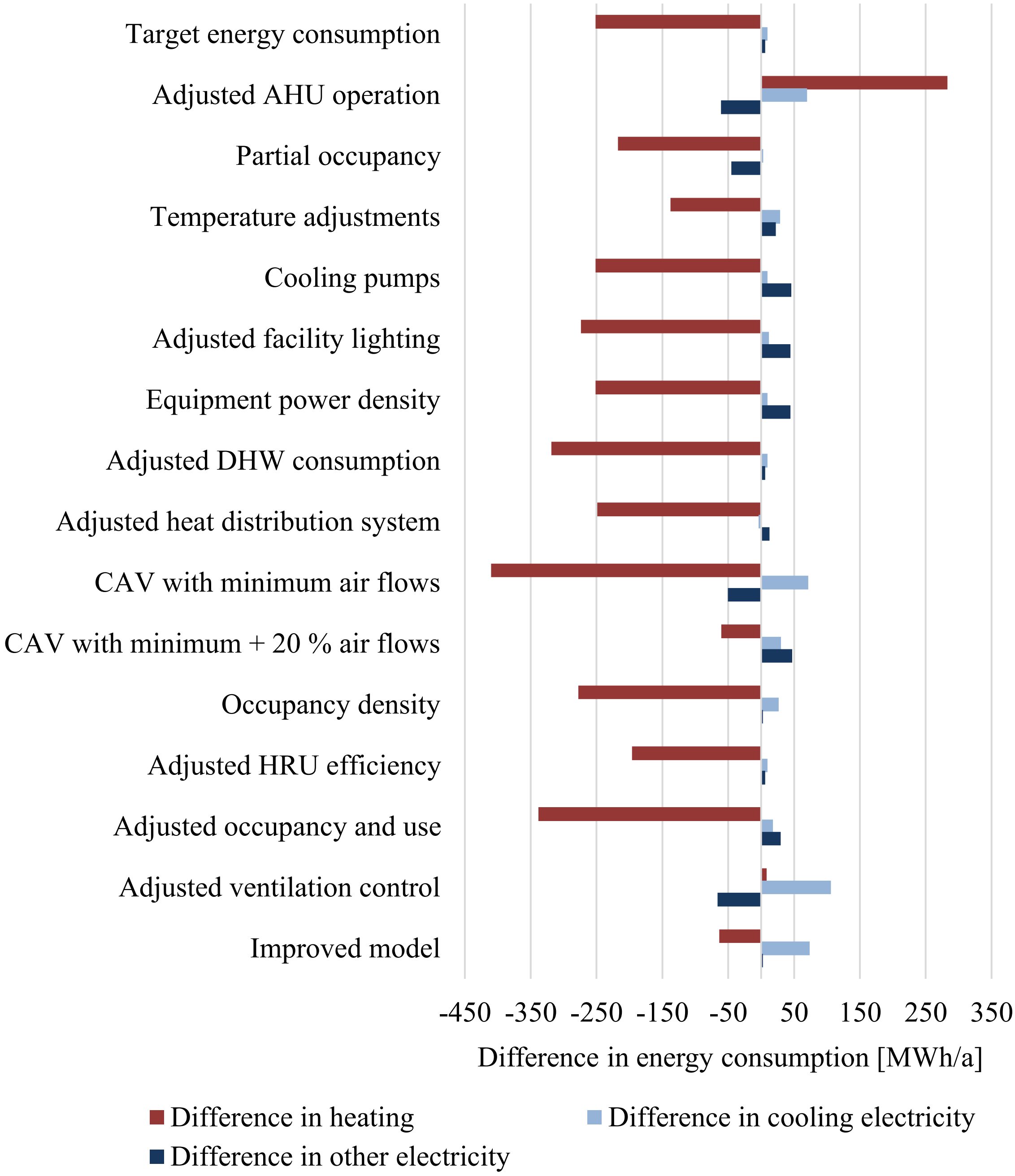

Figure 30. The difference of each adjusted model and the metered consumption in heating, cooling and other electricity consumptions.

The percental contribution of each studied factor on the performance gap according to the reduction of the difference between the predicted and metered consumptions is presented in Figure 31. The three factors with the highest significance in the gap are thus AHU operating schedules, air flows and supply air and room temperature setpoints and schedules, while the least significant studied factors are differences in partial occupancy, occupancy density, facility lighting and heat distribution systems.

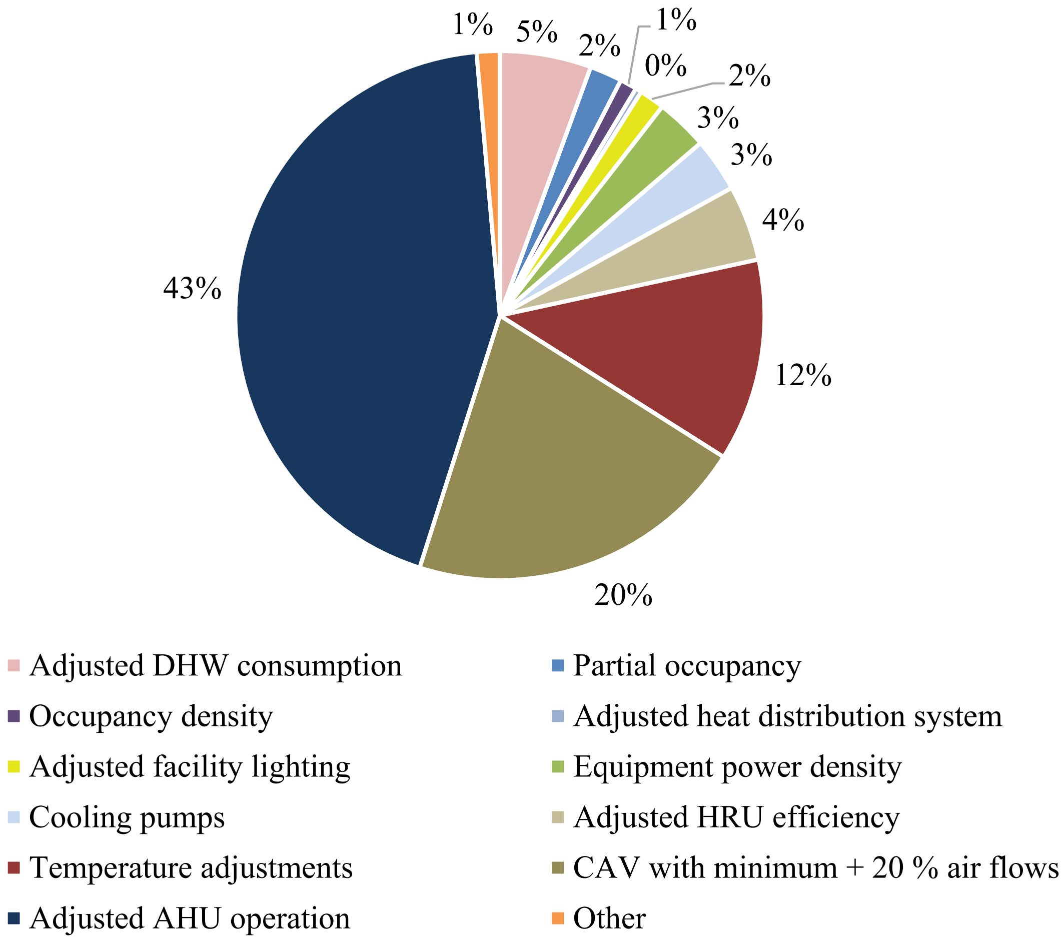

Figure 31. The share of each factor on the total performance gap of 15.2 kWh/m²a in the studied building.

6.2.2 Effects of occupancy and use

In the studied building the differences in facility lighting is 38 MWh/a covering 16 % of the total gap, while tenant lighting is predicted 27 MWh/a lower compensating 12 % of the gap. While, in the public facility spaces, the actual use of lighting during unoccupied hours is the main source of difference and in the tenant spaces the gap is mainly due to partial occupancy of the building with one of eight floors being unoccupied during the first year of operation.

Consequently, the distribution of internal heat gains and loads from lighting is modelled differently than it occurs in the real building, affecting the heat balances of the spaces and thus the heating and cooling demand. Thus, the inaccuracy of the prediction of lighting loads and schedules is one of the important factors forming the gap, despite its total effect on the gap being as low as 5 %.

In addition to the interior lighting, the plug load operation reduced by the partial occupancy of the studied building affects the electricity, heating and cooling demand. However, the power and operating schedules of the plug load in the occupied floors are accurately estimated, since the electricity consumption of tenant equipment in the adjusted model with partial occupancy considered is differing by less than 1 %. Nevertheless, the power demand of the facility equipment is predicted as 27 % lower due to the lack of available documentation regarding building auxiliary systems nominal power use. Adjusting the facility equipment consumption reduces the gap by 4 %-units.

The heating consumption of domestic hot water is initially estimated based on the Finnish Building Code section D3, but the metered consumption is 58 % lower than estimated. Considering the occupancy rate and the suggestions from Motiva (2016), the average water DHW heating consumption for each occupant is 14.5 kWh/person, a when the consumption of the catering kitchen is calculated as 40.4 MWh/a. The combined consideration of occupancy, lighting and equipment schedules as well as DWH increases the gap by 3 %-units while reducing the total heating consumption by 87 MWh/a and increasing the cooling and other electricity consumptions by 8 MWh/a and 24 MWh/a, respectively.

The effect of each adjustment of occupancy and use on each sub-consumption in the studied building is presented in Figure 32. Consequently, the model with combined occupancy and use adjustments predicts equipment and lighting electricity close to the metered consumption and DHW heating as metered, while the difference in space and supply air heating and cooling, fan and pump operation cannot fully be explained with difference in occupancy and use.

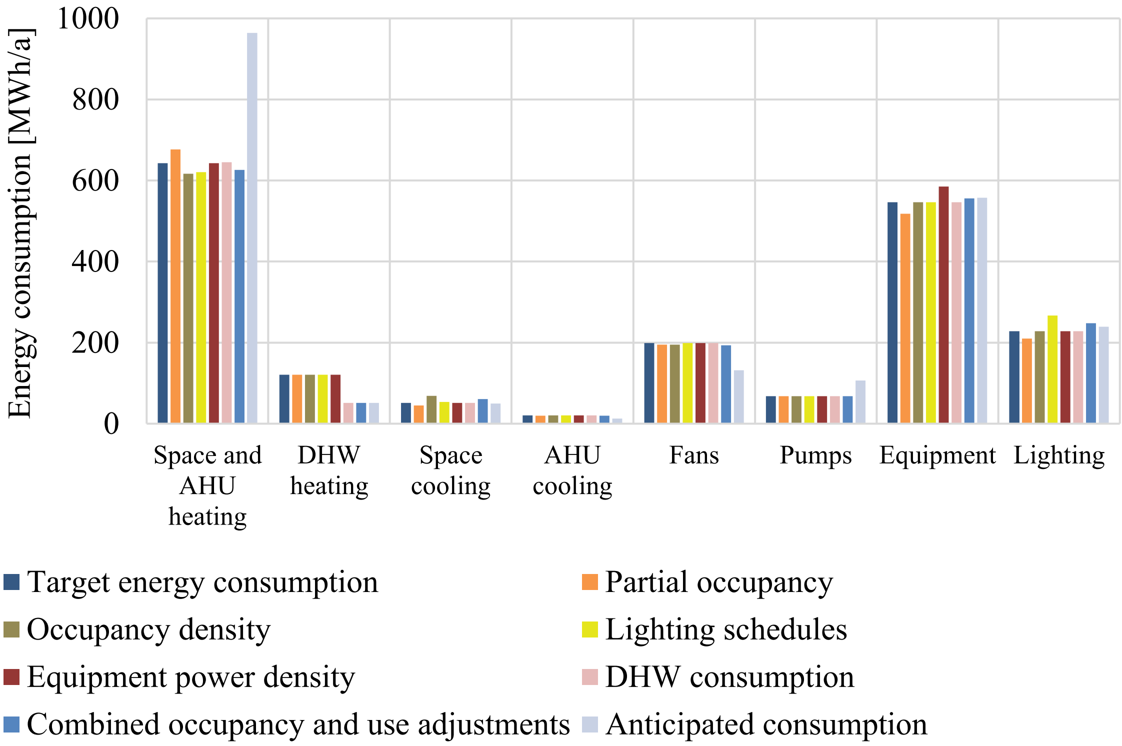

Figure 32. The relation of the energy consumption of each end-use in the models with adjustments regarding occupancy and use with the target energy and the metered consumptions.

6.2.3 Effects of ventilation operation

In addition to the lighting, occupant and plug load schedules, the building use affects the air handling unit operation schedules and air flow rates, supply air and indoor temperature setpoints and schedules as well as the heat recovery efficiency. The effect of each of these adjustments on each sub-consumption in the studied building is shown in Figure 33. As can be seen from the Figure these factors have a high impact on the heating and cooling consumptions as well as fan electricity consumptions, and unlike the occupancy, lighting and plug load adjustments do not affect the DHW heating, equipment and lighting electricity consumptions.

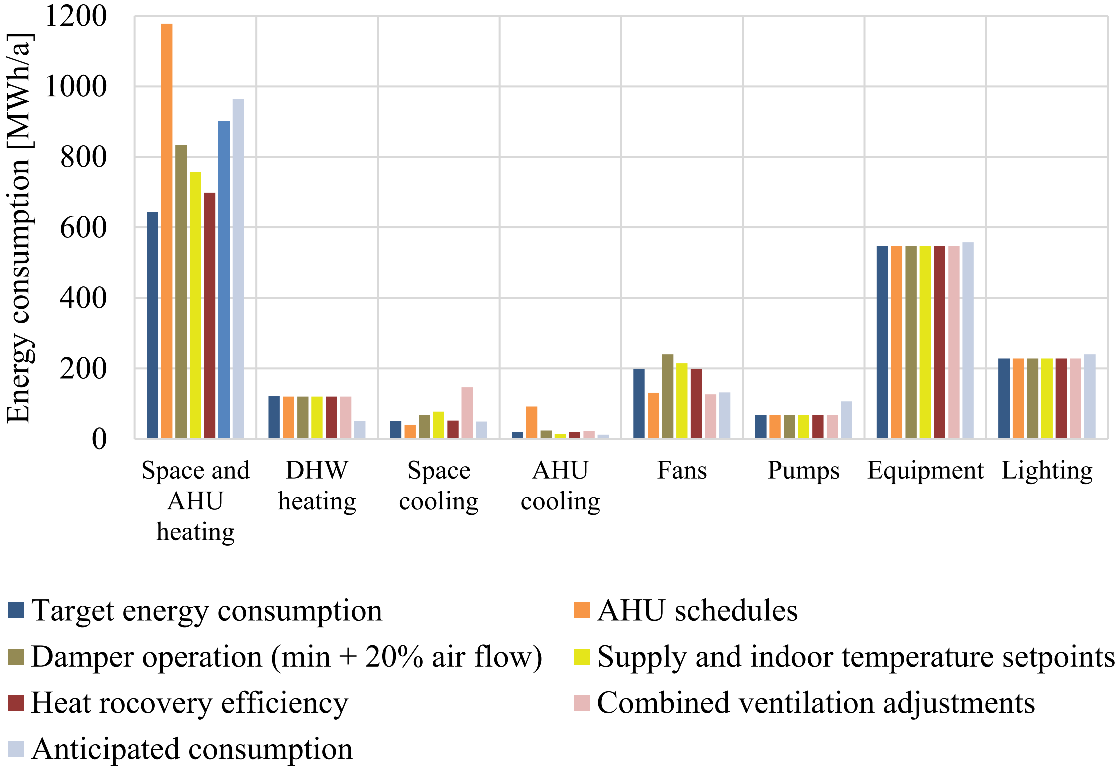

Figure 33. The relation of the energy consumption of each end-use in the models with adjustments regarding use of ventilation with the target energy and the metered consumptions.

The actual operation schedule of each air handling unit in the studied building differs from the design while some schedules are longer and some shorter than designed. However, the overall operation is longer increasing the supply air heating. Additionally, the designed night ventilation in the AHUs serving office and conference rooms is not applied in the actual operation resulting in a significantly lower fan electricity consumption while notably increasing the supply air cooling consumption during the AHU operation, while night time space cooling is not applied.

Resulting from the increased AHU operation combined with higher constant air flows and lower heat recovery efficiency, the supply air and space heating consumption is nearly doubled, the supply air cooling is 2.5 times higher than in the initial model and the fan electricity consumption is reduced by 24 %. The adjustment of the operation schedules of

AHUs is the major factor increasing the total energy consumption, and in particular the heating consumption in the model as shown in Figures 30 and 33.

Since demand control ventilation is not applied in the actual building operation despite its utilization in the design documentation, all spaces are served with constant air flows. However, since the air flows or damper positions are not measured, the actual air flows remain unknown. Two options are modelled, the minimum air flows designed for the hours with no increased ventilation demand and the minimum airflows with an additional 20 % from the difference of the minimum and maximum air flow. As can be seen from Figure 12, the model with the greater air flows represents the metered consumption more accurately. With the adjusted greater air flows, the total performance gap is as low as 1 %, while space and supply air heating and cooling as well as fan electricity consumption exceed the initial model.

The adjustment of indoor and supply air temperature setpoints and schedules increases the space and supply air heating and space cooling consumptions while reducing the supply air cooling consumption. The adjusted model has a 4 % lower total energy consumption than metered, thus reducing the gap significantly. Adjusting the heat recovery unit efficiencies of the three largest air handling units increases the supply air heating consumption resulting in a 8 % lower total energy consumption than metered.

Finally, adjusting all the presented ventilation related measures in the model results in 3 % lower total energy consumption thus providing a more accurate estimate of the building energy use than the initial model or the model with adjusted occupancy and use. The initially most differing end-use, space and supply air heating differs from the metered consumption by merely 1 % and the fan electricity consumption by 10 %. The main differing end uses in the adjusted model are supply air cooling and pump electricity consumption.

6.2.4 Effects of heating and cooling systems

While creating the initial model, the heat distribution method is not modelled, but only considered in the heat distribution efficiency according to Finnish Building Code section D5. However, modelling the realistic heat exchangers into the spaces instead of ideal heaters and coolers decreases the space cooling consumption by 29 % and the supply air heating by 1 % while increasing the space heating consumption by 2 % and supply air cooling consumption by 5 %. The difference in the total energy consumption between the model and the metered consumption is 11 %, which is less than in the initial model. However, the change in the performance gap is minor compared to the ventilation adjustments.

Furthermore, a significant difference in the monthly cooling pump operation is observed between the initial model and the metered consumption. The model assumes ideal cooling pump operation according to the cooling demand, and during the heating season the modelled consumption is practically 0. However, the actual cooling pumps operate throughout the year with a minimum 4 kW base load. Additionally, the cooling pump operation during the cooling period is underpredicted in the initial model. Adjusting the operation of the cooling pumps in the model results in a more accurate prediction of the cooling pump operation and a 9 % lower total energy consumption than metered. The effect of the heat distribution method and cooling pump operation adjustments as well as the final improved model on each subconsumption are presented in Figure 34.

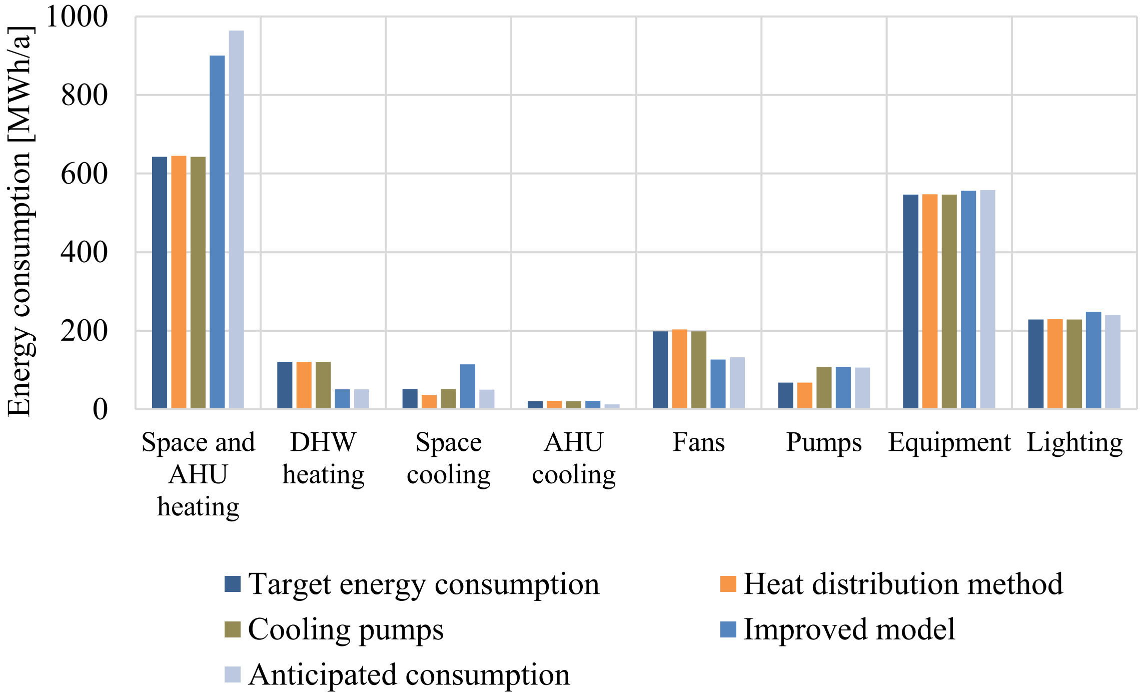

Figure 34. The relation of the energy consumption of each end-use in the models with adjusted cooling pump operation and heat distribution method as well as the model with all available adjustments with the target energy and the metered consumptions.

7 Discussion

In the performed case study of an office building in Helsinki the observed performance gap is 13 %, which lies within the range of -2 % to 30 % from previous studies. The energy performance gap of the building is defined as the relative difference of the metered consumption and the target energy consumption calculated according to the designed operation and occupancy. A negative gap indicates that the metered consumption is lower than estimated while a positive gap indicates a greater metered consumption than estimated. The magnitude of the gap calculated in previous studies and the magnitude suggested by experts correlate and thus the magnitude can be estimated to vary between -2 % to 40 %. Moreover, the majority of estimates predict a lower consumption than metered.

Since the gap in heating energy consumption is the utmost result of the gap forming factors, the factors with high influence on the heating consumption are also the major error causing factors. The significant increase in energy consumption is mainly due to the differing AHU operation schedules but is also significantly affected by the air flows, supply air and heat recovery efficiency and the heat recovery efficiency. Thus, adjustments regarding ventilation have the highest influence on the total heating consumption. Consequently, the model with all the ventilation related adjustments results in a rather accurate model with only 3 % difference from the metered consumption. The underprediction of the total electricity consumption excluding cooling electricity by 1 % and cooling electricity consumption by 13 % are merely significant in the gap formation.

Other studied factors, regarding building occupancy and use as well as heat distribution method and cooling pump operation, have minor influence in the gap and their consideration is less relevant when pursuing an adequate estimate of the upcoming building energy consumption. However, their consideration is necessary when the aim is to close the gap completely. Occupancy and use related measures are more significant in building types with inconstant occupancy such as residential buildings and shopping centers.

Multiple studies including Carbon Trust (2012) and Kampelis et al. (2017) state that poor communication during the design and commissioning phases result in poor modeling and use of the building and its systems. The lack of available information is addressed also in the study of Fedrouk et al. (2015) as one of the significant factors reducing the model inaccuracy. This is relevant also in the case building, the operating schedules, air flows and temperature setpoints are not applied as designed, which may result from inadequate communication between the design team, the building owner and the janitor. Additionally, the installed not utilized control dampers are not installed as designed, possibly due to insufficient communication between the design team and the contractors, thus distorting the model.

As stated by the interviewees the lack of available information during the final design stage regarding especially operating schedules, plug loads and occupancy rates reflects also the accuracy of the created model. Only after adjusting the model with the information available in the operation stage the missing information can be supplemented. However, even when creating the adjusted model, the occupancy schedules and technical details of special spaces remain unavailable as concluded by the interviewed experts.

In the studied building, the unavailable information included also fan curves, power consumption of facility systems such as sign and emergency lighting, security alarm, access control and fire alarm systems. The lack of this information restricted determination of interior heat loads as well as lighting and equipment electricity consumption. Additionally, no building specific information regarding DHW consumption was available neither the number of occupants. Consequently, the lack of knowledge during the design phase reflected the level of assumptions made and thus also the model accuracy.

Furthermore, the reliability of the design documentation in creation of a reliable model describing the final use of the building is questionable as the actual operation may not correlate with the design. Especially building operation parameters, such as operating schedules and setpoints as well as ventilation operation schedules, are eventually adjusted during the operation and may not consider the initial design. Therefore, as the ventilation schedules are typically longer than designed according to the previous experience of the interviewed experts and the results of this study, while predicting the future energy use of the building, the operation schedules of the AHUs could be slightly overestimated. In case a night time ventilation is designed, an additional case with no night ventilation could be performed in order to have knowledge about the possible higher consumptions. A slight overestimation of operating schedules could be applied also in the occupancy, lighting and equipment loads, as the actual schedules often exceed the predicted ones. However, the influence of the lighting and plug loads is minor compared to the ventilation control adjustments and the necessity of such overestimations should be considered case-specifically.

Previous studies such as Kampelis et al. (2017), Menezes et al. (2011) and Carbon Trust (2012) highlight the importance of predictability of occupant, receptacle equipment and lighting loads and schedules. These studies show generally higher metered heating and electricity consumptions in particular when manual controls for plug loads and lighting are accessed to the occupants. Likewise, all interviewed experts claim incorrect prediction of occupant related loads and schedules as one of the most significant factor in the formation of the energy performance gap.

Similarly to the previous studies and the previous experience of the interviewed experts, in the studied office building the actual building use differs from the estimates made in the created model regarding lighting schedules and occupancy density and distribution. While stochastic models for prediction of the behavior of occupants exist, they need further improvement as they do not describe the reality according to Ahn et al. (2017). Occupancy sensors for example could be utilized in creation of improved models. In this study no such models are used, but the occupancy is estimated according to a typical office building use.

The use of the building can differ also in the building automation system control and as found in the studies of Fedrouk et al. (2015) and Salehi et al. (2015), it is a significant factor in the gap formation. Accordingly, in the studied building the ventilation operation differing from the design resulted in the majority of the gap. Moreover, the unavailability of actual operating details, such as heat recovery, air flows, SFP and fan curves in this study, as well as the thermal properties of the used building structures, COP of the cooling equipment and possible previous temporary changes in the building automation and operation increases the uncertainty of the model. As in this study, most such systems affect especially the heating demand and result in a great mismatch between the simulated and metered consumption when not used as designed.

Tuning the building automation system settings differently than designed ignores the designed operating patterns and goals set regarding the building life-cycle and energy use. This reduces the possibilities enabled by the target energy consumption as pointed by Vuolle (2017) and as in the studied building increases the total energy consumption from the estimated optimal level thus also increasing the costs from energy use. Nevertheless, malfunctioning of the technical building systems cannot be predicted during the design phase and therefore it is a source of errors in the target energy consumption. This is addressed by Nevala (2015) and it is present also in the studied case building as abnormal operation of cooling pumps and operating the variable air systems with constant air flows. As the malfunctioning of systems or change in operation capacity cannot be predicted, they inevitably cause a gap. On contrary, adjusting the operation by the property manager can be affected by proper communication. Optimization of building systems' operation should be performed during the design stage and no long-term changes should be enabled to the maintenance.

Part of the gap can be explained with an inadequate modeling procedure. The simulation software assumes that all processes are ideal and calculate optimally for example the utilization of internal heat gains. In practice, however, the heating and cooling systems respond slowly to the changes in indoor temperature and therefore when internal heat gains increase, the decrease in heating is not obvious resulting in underprediction of the heating demand. Additionally, the fan curves for example are too ideally assumed by the model. Such differences however cannot explain a significant part of the error, since as in the studied building the majority of errors consist of different use and operation than designed as well as malfunctioning of systems.

Finally, the energy performance gap is partly also modeler dependent and relates to the estimates formed. Therefore, further investigation and experience is needed on the energy performance gap in order to improve the estimates and better predict the anticipated consumption. In the case study, the modeler and her possible modelling errors affect the results of the simulation while important modelling errors are avoided with analysis and consideration of the results and correction of the model, when needed.

While the performance gap depends on factors that can be divided into modeler, software, design documentation and actual use related, the majority of factors relate to multiple sources. An inaccurately modelled occupancy pattern differs due to the actual use of the building differing from the predicted, the false estimates made by the modeler and the lack of available information during the design phase. Likewise, a false consumption estimate of space heating relates to the actual installation and use of the heating systems, the level of detail in the design documentation, the estimates and level of details modelled by the modeler as well as the accuracy of the simulation software, for example considering the adjustability and delay of response of the system.

Despite the significant differences between the actual building operation and the initial model, several factors are modelled accurately. The space type division, service areas of the different AHUs and lighting power densities are modelled as in the actual building. Additionally, the predicted air infiltration rate 1.0 m^3/ m^2s is equal to the measured air infiltration rate of the building. The effect of the annual weather variation in heating is considered by normalizing the metered consumption to correspond with the weather data of the reference year 2012 used in the model. Should the effect of these factors be examined, a further study is needed.

Due to the partial occupancy, the domestic hot water consumption is reduced. However, as the metered DHW heating consumption is 58 % lower than estimated, the used general building type and area dependent suggestions given in the Finnish Building Code D3 do not represent the actual consumption in the studied building. A more accurate estimate of the building can be created based on the number of full-time occupants, when such information is known. In the studied building the occupant-specific consumption of DHW is 86 – 117 kWh/person, a representing 1.4 – 1.9 m^3/person, a. It should be noted however, that the consumption may vary in different buildings and further study cases are required to determine a good average estimate for office buildings in general. The mismatch of the DHW consumption verifies the criticizing of Nevala (2017) towards the appropriacy of use of pre-defined area specific measures for the estimation of different consumptions.

As the final model of the case building is left with a slight gap, there are factors affecting the gap that are not noted in this study. Such factors include i.a. heating pump operation, cooling efficiency and actual maximal cooling power, application of manual shading and its schedules, heat storage effect of interior furniture and thermal properties of interior and exterior structures. However, since the magnitude of the obtained gap of the improved model in both heating and general electricity consumption is close to the metered consumption, the effect of the unstudied factors can be assumed to be minor or correctly modelled in the case building.

Furthermore, it should be noted, that this study focuses on a single office building in Finland. Should information of other building types and locations be investigated, additional study is required, and the outcomes of this study cannot be fully utilized. The accurate prediction of the energy consumption would require detailed investigation on the building in question and understanding of the exact operating procedures. Thus, complete closing of the gap is not possible before the actual building operation.

In the improved model the major differing end-use is space cooling electricity. Unlike for heating energy, there is no standardized method for cooling energy normalization according to the year dependent climate conditions. While heating can at a rough level be adjusted based on monthly heating degree days, cooling is not adjusted. Due to its dependence on the ambient outdoor temperature, the simulated and anticipated cooling consumptions would differ also in a situation with a simulation perfectly matching the actual building, if the simulation is performed in a different time period than the actual use. Thus, the difference in weather may explain also part of the remaining gap in the improved model of the studied building, especially in cooling electricity.

The different cooling demand affects indirectly also the cooling pump electricity consumption, supply air cooling, air flows and fan electricity in variable air volume systems. Additionally, especially with intermediate outdoor temperatures, cooling the space may affect the heating demand and vice versa. Therefore, the difference in cooling electricity consumption as well as electricity and heating consumption may also be partly a result of unnormalized cooling or more precisely unrealistic climatic conditions.

Cooling consumption may also differ due to modelling faults or malfunctioning of the cooling systems. As cooling is overpredicted especially during the cooling season, the actual maximal cooling capacity may be less or the COP may be higher than the designed values resulting in a lower cooling electricity consumption in practice. A poor installation of space cooling devices or a smaller number of devices can also result in a lower cooling consumption than predicted.

In the performed case study, the energy performance gap is studied in an annual and monthly level, but there may be differences in a more detailed level such as daily or hourly. Thus, should a more accurate study be performed, the studied time periods shall be decreased. However, the monthly level allows to see the major factors and the overall magnitude of the energy performance gap as aimed in this study. Nevertheless, the used simulation software IDA-ICE allows an hourly dynamic calculation with a high accuracy, thus enabling both the rough and small-scale study.

In order to locate the exact factors of the energy performance gap, sufficient submetering is needed. The lack of sub-metering restricts the level of accuracy of the results and the possible findings. In the studied case building sub-metering is relatively comprehensive. However, with wider submetering a more inclusive investigation can be performed. Additionally, the lack of logged data restricted the information available to adjust the model. Thus, should a further investigation on the gap be performed, the chosen building shall have a sufficient level of data logging and sub-metering and all automation and logging calculations shall be verified.

While the studied performance gap describes the difference between the simulated and metered consumption, the accuracy of the metered consumption is not accounted. However, metering faults are present also in the studied building, which is why some available sub-meters are not utilized in the study. If such errors are not known and false metering values are used in determination of the metered consumption, these errors affect the gap as the simulation assumes perfectly accurate metering and sub-metering. Therefore, incongruent metering shall be identified as one of the factors affecting the gap, while finding its magnitude and relation on the gap would require further investigation.

Special effort should be invested in education of the property managers to operate the systems as designed and designers should be informed of the practical limitations. Further study on efficient communication between the parties as well as the reasons for operation of systems differently than designed is useful in lowering the gap. Additionally, further studies on the reasons of the gap should be performed in various locations and to multiple building types.

8 Conclusions

The energy performance gap is significant even in office buildings with relatively high predictability of occupancy schedules. Previous studies and the interviewed experts suggest a gap varying from -2 % to 40 %. A case study is performed in an office building in Finland and the obtained performance gap is 13 % verifying the results from the previous studies. In the studied building the majority, 94 % of the gap, results from falsely predicted heating consumption as due to the cold climate of Finland, the heating consumption of the studied building covers 40 % of the total energy consumption.

In the case study, the major factors influencing the gap are mismatching operation schedules for ventilation, air flows, supply air- and room air temperatures, heat recovery efficiency and domestic water consumption contributing to over 50 % of the gap. On contrary, occupancy related factors as well as factors concerning other technical systems of the building show a minor effect on the gap. The combined adjustment of all ventilation related factors reduced the gap from 13 % to 2 %, thus providing a rather accurate prediction of the consumption.

Adjusting all the studied parameters results in a model with only 1 % difference from the metered consumptions indicating that all relevant and major factors influencing the gap in the studied building are included in the study. However, the remaining gap is partly due to high uncertainties in the estimates made due to the missing information as well as the factors that are not included in the study. Among these factors are heating pump operation, cooling efficiency and actual maximal cooling power, application of manual shading and its schedules, the heat storage effect of interior furniture and thermal properties of interior and exterior structures.

The factors resulting in a performance gap can be divided into modeler, software, design documentation and actual use related. However, the majority of factors relate to multiple sources. Factors related to actual use and design documentation are addressed by previous studies and experts and showed the highest effect in this study as well. Additionally, the lack of communication between different groups in every part of the design and construction project is acknowledged in previous studies as an important reason for mismatches between design and application. Similarly, it is acknowledged for one of the highest mismatches and inaccuracies in the studied building, the poor installation of control dampers.

Due to the generally underestimated AHU and occupancy related schedules and the high impact of the AHU schedules, an overestimation could be included in the target energy consumption models of office buildings. Especially, when night ventilation is designed, the effect of its rejection should be reported to the building owner as it results in a significantly higher total energy consumption as can be concluded from the performed study.

The performance gap represents the difference between the target energy consumption and the metered consumption as a percentage of the target energy consumption. It covers all the purchased heating, cooling and electricity consumption of the building and thus does not describe the exact differences of each energy subsystem. The observation accuracy of the estimates for each end-use depends on the level of availability for submetered consumptions. It should be noted as well that a low performance gap does not necessarily indicate an accurate model, since the gaps of different sub-consumptions may compensate each other resulting even in a zero performance gap in a completely inaccurate model. Therefore, more precise investigation between heating, cooling and electricity consumptions and more preferably each subconsumption ensures the accurate calibration of the model.

Should the gap be comprehensively closed, further study is needed on the topic, since this study is performed to a single office building and cannot be fully utilized in other buildings. However, as the noted most significant factors relate to building use and lack of design documentation, which are accused in several previous studies as well as by the interviewed experts, such topics should be modelled more thoughtfully in order to achieve a gap as low as possible.

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Appendices

Appendix 1. The applications, advantages and disadvantages of different metering techniques

The applications, advantages and disadvantages of different metering techniques as explained by Parker (2015).

Criteria	One-Time/Spot Measurements	Run-Time Measurements	Short-Term Measurements	Long-Term Measurements
Unique Application	Measure instaneous power, short-term energy use, equipment performance, or loading	Measure run times of fans and pumps, or the operational characteristics of heating, cooling or lighting systems	Verify performance, initiate trending, or validate efficiency improvement	Measure variances in weather, occupant behavior, or other operating conditions. Benchmark the resource use of the building over time
Advantage(s)	Ease of use Non-intrusive Fast results	Relatively easy of use Non-intrusive Useful for constant load devices	Can quantify magnitude and duration Relatively fast results	Highest accuracy Can quantify magnitude and duration Captures most variance
Disadvantage(s)	Low accuracy Limited application Measures single operating parameter	Limited operation Measures single operating parameter Requires additional calculations/assumptions	Mid-level accuracy Limited application Seasonal or occupancy variance deficient More difficult to install	Most difficult to install and monitor Time duration for result availability
Cost	Lowest	Low	Mid	High

Appendix 2. A caption of previous studies on the energy performance gap

Study	Case	Building type	Location	Performance gap [%]	Reasons
Carbon Trust 2012	28 Cases average	Multiple	Great Britain	avg. 16%	Inadequate building design predictions due to system complexity, inadequate commissioning, improper operation of the building
Bordass et al. 2001	23 Cases average	Multiple	Great Britain	avg. ca. 50 %	Lack of feedback
Nevala 2015	3 Cases average	Multiple	Finland	up to 25 %	Poor exploitation of building automation systems
Kampelis et al. 2017	Leaf Lab	Industrial	Italy	0.1 %	-
Kampelis et al. 2017	NTL	Office	Cyprus	-2.3 %	Lack of useful information, interpreting of information, communications, feedback and interaction
De Wilde 2014	The Roland Levinsky Building	Office	Great Britain	30 % (el.) -5 % (heat)	False estimate of plug loads
Menezes et al. 2011	-	Office	Great Britain	corrected by 3 % with POE	Unknown occupancy patterns and behaviour, false lighting loads
Fedrouk et al. 2015	CIRS	University	Canada	29.1 % (el.) -57.8 % (heat)	Commissioning, controls, fixes, technical modelling errors, monitoring faults, poor system boundary definition, pumps and fans, lighting and plug load, operating sequances

Study	Case	Building type	Location	Performance gap [%]	Reasons
Ruusala 2015	22 Cases average	School and kindergarten	Finland	41.3 % (tot.) 15.4 % (el.) 68.7 % (heat)	-
Zero Carbon Hub 2014	97 Cases average	Residential	Great Britain	DER deviation 17 %	Lack of knowledge, communication and management
Kampelis et al. 2017	Leaf House	Residential	Italy	177.6 %	Energy for lighting and appliances not considered, occupant behaviour

Appendix 3. The interview questions

1. Asteikolla 1-5 kuinka tuttu ”performance gap” termi on sinulle?

2. Kuinka pitkä simulointikokemus sinulla on ajallisesti?

3. Mikä on koulutustaustasi?

4. Mitä ohjelmia olet käyttänyt energiasimuloinnissa ja minkälaisia kokemuksia sinulla on niistä?

5. Millainen kokemus sinulla on tavoitekulutusten laskennasta?

6. Mitä laskennan kannalta oleellisia lähtötietoja ei kokemustesi perusteella useimmiten saada

- luonnossuunnitteluvaiheessa
- toteutussuunnitteluvaiheessa
- vastaanottovaiheessa?

7. Entä mitä tietoja vastaavissa vaiheissa yleensä saadaan?

8. Saatko valaistuksen tehotiedot, laitteiden tehotiedot, sulatusten tehot, pumppujen käyntiajat, yleiset käyttöajat, käyttöprofiilit jne. suunnitelmista tai käyttäjältä vai arvioitko ne kokemusperäisesti. Mitkä tekijät (myös näiden lisäksi) arvioit yleensä kokemusperäisesti?

9. Perustuvatko laskennassa käyttämäsi lähtöarvot, joita et saa suunnittelijalta

a) Suomen Rakennusmääräyskokoelmaan

b) Kokemuksiisi aiemmista kohteista

c) Muuhun (Mihin?)

10. Mitä asioita on mielestäsi vaikeinta huomioida tavoitekulutuslaskennan energiasimuloinnissa? Miksi?

11. Oletko ollut mukana seuraamassa toteutuneita kulutuksia ja päivittämässä tavoitekulutuslaskentaa rakennusten käyttöjaksolla? Jos olet, mitä laskennan kannalta oleellisia lähtötietoja on haastava saada täsmäämään todellisessa käytössä ja laskennassa?

12. Kuinka suuren *performance gap*in arvioit olevan Suomalaisissa toimistorakennuksissa?

13. Mikä on oma käsityksesi siitä, mistä tekijöistä *performance gap* yleensä johtuu? Ovatko tietyt syyt yleisempiä tietyissä rakennustyypeissä, erityisesti toimistorakennuksissa?

14. Muita huomioita

Appendix 4. Supply air temperatures of AHUs in the studied building

AHU	Designed supply air temperature	Actual supply air temperature
301TK – 303 TK Offices	19 ^{0}C, when outdoor temperature is < -10 ^{0}C; 17 ^{0}C, when outdoor temperature is > 20 ^{0}C; linearly dependable on the temperature, when outdoor temperature is -10 ^{0}C < and <20 ^{0}C	19 ^{0}C, when outdoor temperature is < 21 ^{0}C; 15 ^{0}C, when outdoor temperature is > 22 ^{0}C; linearly dependable on the temperature, when outdoor temperature is 21 ^{0}C < and <22 ^{0}C
304TK Kitchen	Same as in 301 – 303 TK	20 ^{0}C, when outdoor temperature is < 20 ^{0}C; 15 ^{0}C, when outdoor temperature is > 24 ^{0}C; linearly dependable on the temperature, when outdoor temperature is 20 ^{0}C < and <24 ^{0}C
305TK Restaurant	Same as in 301 – 303 TK	21 ^{0}C, when outdoor temperature is < 20 ^{0}C; 15 ^{0}C, when outdoor temperature is > 24 ^{0}C; linearly dependable on the temperature, when outdoor temperature is 20 ^{0}C < and <24 ^{0}C
306TK Auxiliary spaces	Same as in 301 – 303 TK	23 ^{0}C, when outdoor temperature is < 21 ^{0}C; 18 ^{0}C, when outdoor temperature is > 23 ^{0}C; linearly dependable on the temperature, when outdoor temperature is 21 ^{0}C < and <23 ^{0}C
307TK Restrooms	Same as in 301 – 303 TK	22 ^{0}C, when outdoor temperature is < 21 ^{0}C; 15 ^{0}C, when outdoor temperature is > 23 ^{0}C; linearly dependable on the temperature, when outdoor temperature is 21 ^{0}C < and <23 ^{0}C
308TK Stairway	Constant 17 ^{0}C	Constant 17 ^{0}C
309TK Stairway	Constant 17 ^{0}C	Constant 17 ^{0}C
310TK Stairway	Constant 17 ^{0}C	Constant 17 ^{0}C
311TK Technical spaces	Constant 17 ^{0}C	Constant 17 ^{0}C